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REPORT NO. 1118
OCTOBER 1960

FORECASTING THE FOCUS OF AIR BLASTS
DUE TO METEOROLOGICAL CONDITIONS
IN THE LOWER ATMOSPHERE

Beauregard Perkins, Jr.
Paul H. Lorrain
William H. Townsend

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND
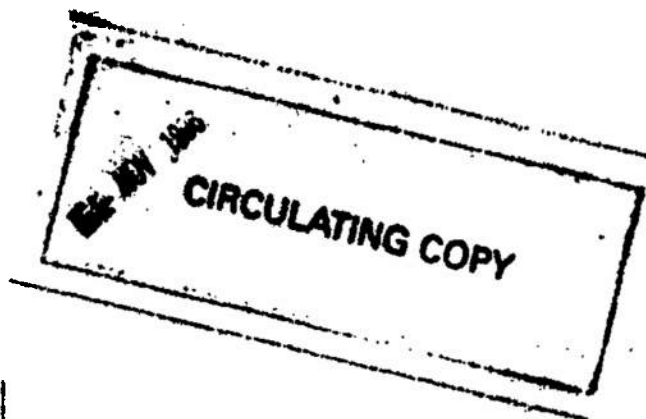
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B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

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Terminal Ballistics Laboratory

A B E R D E E N   P R O V I N G   G R O U N D,   M A R Y L A N D

TABLE OF CONTENTS

Page 27. Figure 10 - Sample Data Sheet

Top two numbers in Columns 3, 4 and 5 should read:

3	4	5
Wind Direction From True North (Degrees)	Angle With Azimuth γ (Degrees)	Cos γ
300	94	-.07
012	166	-.97

BALLISTIC RESEARCH LABORATORIES

REPORT NO. 1118

BPerkins,Jr./PHLorrain/
WHTownsend/rac
Aberdeen Proving Ground, Md.
October 1960

FORECASTING THE FOCUS OF AIR BLASTS DUE TO METEOROLOGICAL CONDITIONS IN THE LOWER ATMOSPHERE

ABSTRACT

Whenever explosions are used in testing or in experimental procedures, the sound waves that go beyond the limits of the installation may cause complaints of annoyance or damage from otherwise good neighbors. This is due to focusing of the sound waves caused by the meteorological conditions at the time of the explosion.

The theory of the propagation of sound through the atmosphere is given briefly. The conditions in the atmosphere which cause the sound to be focused are velocity gradients produced by variations with altitude of humidity, air temperature, and wind velocity. A simple method is described for evaluating these factors and forecasting the location of a focus, if one is to be expected, as well as the intensity of the sound at the focus.

This technique has been employed successfully at Aberdeen Proving Ground for three years during which time the complaints have been greatly reduced.

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ACKNOWLEDGEMENTS

LIST OF FIGURES

BACKGROUND

At every Department of Defense establishment where testing operations involve the explosion of H.E. charges outdoors, there are frequent complaints of annoyance or claims for damage from persons living in contiguous areas. The complaints of annoyance are often justified; the damage claims are often unjustified. Both can be reduced or avoided entirely.

The refraction of sound waves produced by the meteorological conditions between the earth's surface and the elevation of 10,000 to 12,000 feet may cause the sound waves produced by explosions at or above the surface of the ground to be focused near homes in the vicinity of the testing area. This phenomenon may be annoying; however, it is doubtful that any damage to walls or window glass will be caused by air blast at distances greater than a few miles from any but very large explosions (100 or more pounds of high explosive).

The refraction of the sound waves is due to the presence of vertical gradients of the velocity of sound through the air $(\frac{dv}{dy})$ where v is the velocity of sound and y is the altitude. Since the velocity of sound in air depends on temperature, humidity, and the wind, the vertical gradient will depend on variations of these factors with altitude.

One of the earliest papers on the refraction of sound due to meteorological conditions was presented to the Royal Society of London about 1906 as a result of the firing of guns during the funeral of Queen Victoria. The easily recognized noise resulting from the rythmic firing of the guns was heard in London and also far to the north but the two areas were separated by a zone of silence. This experience was explained by refraction due to a wind, directed to the north, with a large wind gradient existing at high altitudes. Since that time, about sixty papers have been published on this subject. Everett F. Cox[1], in his treatment

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[1]Numerals refer to references listed at end of the report.

of upper air temperatures as measured at the demolition of Helgoland, has reviewed the salient facts and presented an excellent bibliography of the important contributions.

In the present paper, nothing has been added to the classical theory of propagation; however, an operation procedure is described that permits the meteorological conditions to be quickly evaluated and the cause of complaints from contiguous areas reduced to a minimum.

BASIC THEORY

As stated previously, the velocity of sound in the atmosphere depends on temperature, humidity, and wind. Experience shows that the temperature of the lower atmosphere at Aberdeen Proving Ground may vary through a range of 20 to 30°C between the surface and an altitude of 10,000 feet, causing a change in velocity of sound of 40 to 60 feet per second. In this same region, the wind may vary from 0 to 45 or 60 feet per second. Although the change in relative humidity can be as large as 50%, such a change can affect the velocity of sound by only about 1 foot per second. Since 1 foot per second is less than the error in our determination of wind velocities, the effect of changes in humidity can be neglected without noticeable error.

When the problem of devising a simple but safe set of guidance rules for firing at Aberdeen Proving Ground was given to the Ballistic Research Laboratories, a study was made of the meteorological conditions prevailing in the vicinity of Aberdeen on those days when complaints had been registered. Of twenty-six cases, in all but one, there was a strong wind increasing in velocity at altitudes of about two or three thousand feet up to eight or ten thousand feet. The wind was in general from the point of detonation toward the point of complaint. This fact was taken as sufficient evidence that any guidance rules for the Aberdeen Proving Ground area should include consideration of wind effects in addition to the effect of temperature on the propagation of the sound waves. Thus velocity gradients are based on an algebraic sum of the temperature effect and the wind effect at each altitude. The temperature effect is of course a scalar quantity and is the same in all directions, whereas the wind effect is a vector quantity and is a function of direction. Before describing how the temperature and wind effects can be calculated, the nature of the paths of sound waves will be reviewed briefly.

When an explosion occurs at the surface of the ground, a diverging shock front starts at the point of explosion and spreads in all directions in the hemisphere above the surface of the ground. The shock waves degenerate to sound waves quite rapidly and it is sufficient for

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the purpose of this study to consider only the propagation of sound waves.

The paths of the various parts of the wave front can be depicted by rays emanating in all directions from the center of the explosion. One of these rays will start from the source making an angle θ with the horizontal. Then at the surface

$$y' = \frac{dy}{dx} = \tan \theta$$

where x and y are the horizontal and verticle coordinates. If θ_y is the angle between the ray and the horizontal at any altitude y:

$$y' = \frac{dy}{dx} = \tan \theta_y \qquad (1)$$

and

$$y'' = \frac{d^2y}{dx^2} = \frac{d(\tan \theta_y)}{dx} \qquad (2)$$

If the velocity of sound varies with altitude, the angle θ will vary according to Snell's law such that, if V_y is the velocity at altitude y, then

$$\frac{\cos \theta_y}{V_y} = \text{a constant} = C \qquad (3)$$

or

$$\cos \theta_y = CV_y \qquad (4)$$

from (1)

$$y' = \frac{\sin \theta_y}{\cos \theta_y} \qquad (5)$$

from (4) and (5)

$$y' = \frac{\sqrt{1 - (CV_y)^2}}{CV_y} \qquad (6)$$

or

$$y' = \sqrt{\left[\frac{1}{CV_y}\right]^2 - 1} \qquad (7)$$

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and
$$y'' = \frac{-1}{c^2 V_y{}^3} \frac{dV_y}{dy}$$

$$y'' = \frac{-1}{V_y \cos^2 \theta_y} \frac{dV_y}{dy} \tag{8}$$

$$= \frac{-1}{V_y} (\sec^2 \theta_y) \frac{dV_y}{dy} \tag{9}$$

$$= \frac{1}{V_y} \left[1 - (y')^2\right] \frac{dV_y}{dy} \tag{10}$$

If $\frac{dV_y}{dy}$ = a constant K (the vertical velocity gradient) and if V_1 = velocity at the ground surface, then

$$V_y = V_1 + Ky \tag{11}$$

$$= K \left(\frac{V_1}{K} + y \right) \tag{12}$$

and

$$y'' = - \left[\frac{1}{K \left(\frac{V_1}{K} + y \right)} \right] \left[1 + (y')^2\right] K$$

$$= - \left[\frac{1 + (y')^2}{\frac{V_1}{K} + y} \right] \tag{13}$$

The solution of equation 13 (see references 1, 2, and 3) represents the path of propagation with least time between two points:

$$(x + C_2)^2 + (y + \frac{V_1}{K})^2 = C_1{}^2 \tag{14}$$

in which C_1 and C_2 are constants of integration, and x and y are the cartesian coordinates of the points along the ray path. Equation 14 represents a circle the center of which is on a line below the ground surface a distance equal to V_1/K. The parameter C_1 is the radius of

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the circle and C_2 is the horizontal distance from the origin of co-
ordinates to the center of the circle. In Figure 1 are shown the paths
of several rays starting at the source with different angles of departure.
For a negative gradient the path of the sound wave would be the arc of a
circle curving upward, the center of the circle being on a line above the
ground surface at a distance equal to V_1/K.

Variations with altitude of either the rate of change in air tem-
perature or the rate of change in wind velocity will change the value of
the gradient K and therefore the curvature and direction of the cor-
responding arc will change accordingly. At the boundary between layers
having different values of K there will be a layer of transition in which
the conditions gradually change from those of one layer to those of the
other. In this transition layer the path of a ray gradually changes from
the arc determined by the velocity gradient in the layer from which the
ray is emerging to the arc determined by the gradient of the layer being
entered. Figure 2 shows a typical graph of sound velocity versus alti-
tude and Figure 3 shows the paths of the rays resulting from the gradients
in Figure 2. As indicated above, the curvature of the paths in any layer
depends on the gradient in the layer.

For a ray to be refracted to the surface from any layer, the maximum
velocity attained in that layer must equal or exceed the velocity at all
points in the medium nearer the surface of the ground.

If the ray path is confined to a medium in which only a single
velocity gradient exists the horizontal distance traversed by a given
ray (i.e. the range) can be most simply calculated by plane geometry.
In Figure 4 a ray path is shown leaving the origin at an angle θ, rising
in an arc to an altitude y and returning to the surface at a horizontal
distance R from the origin.

In the figure,

$$\tan \theta = \frac{R/2}{V_1/K}$$

or $$R = 2 \, (V_1/K) \, \tan \theta$$
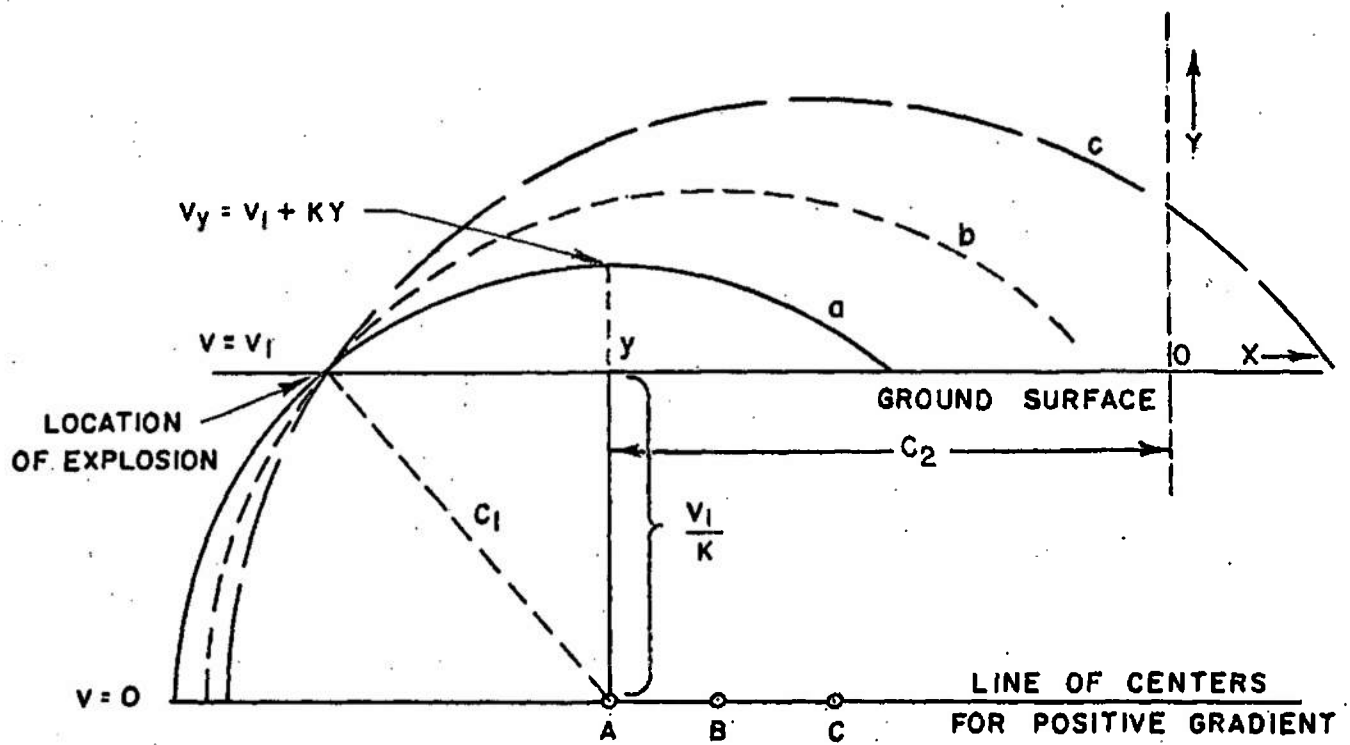
FIG. I – PLOT OF EQUATION 14 FOR VARIOUS VALUES OF C_1
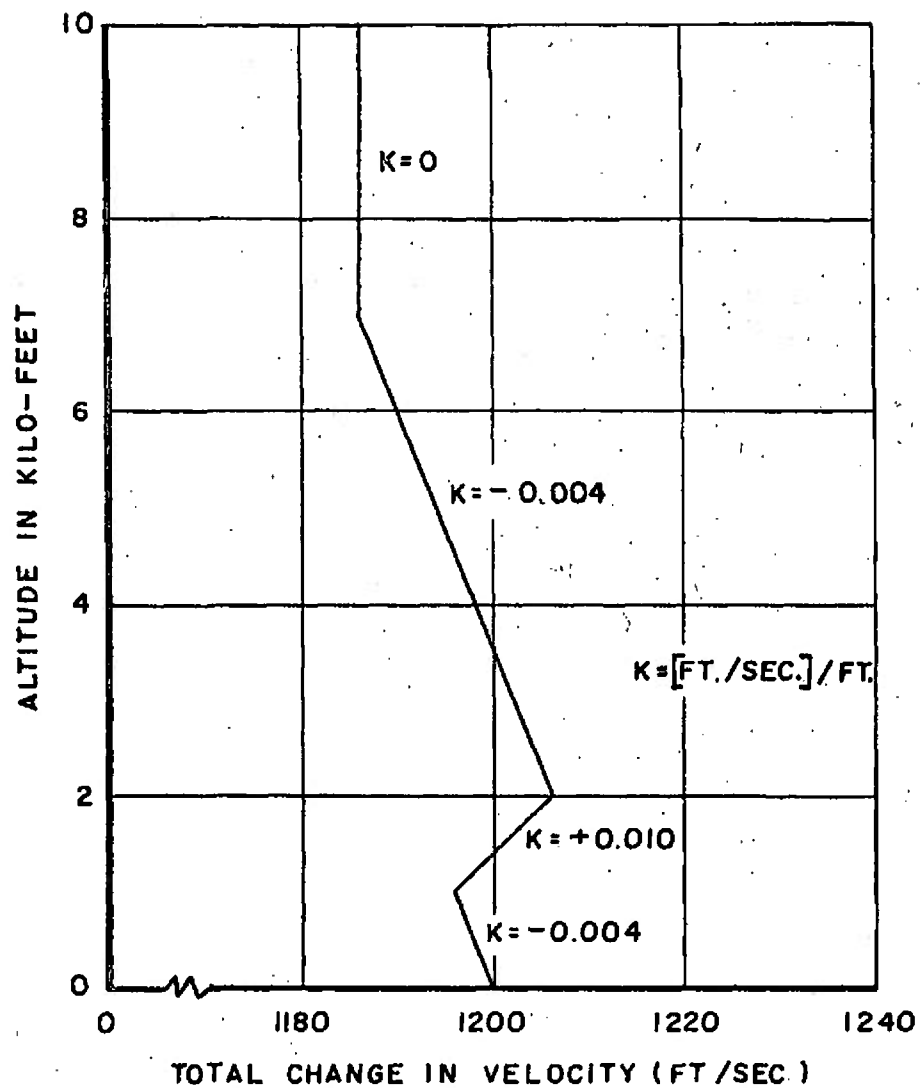i.e. FOR DIFFERENT ANGLES OF DEPARTURE

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FIG 2-TOTAL CHANGE IN VELOCITY vs. ALTITUDE
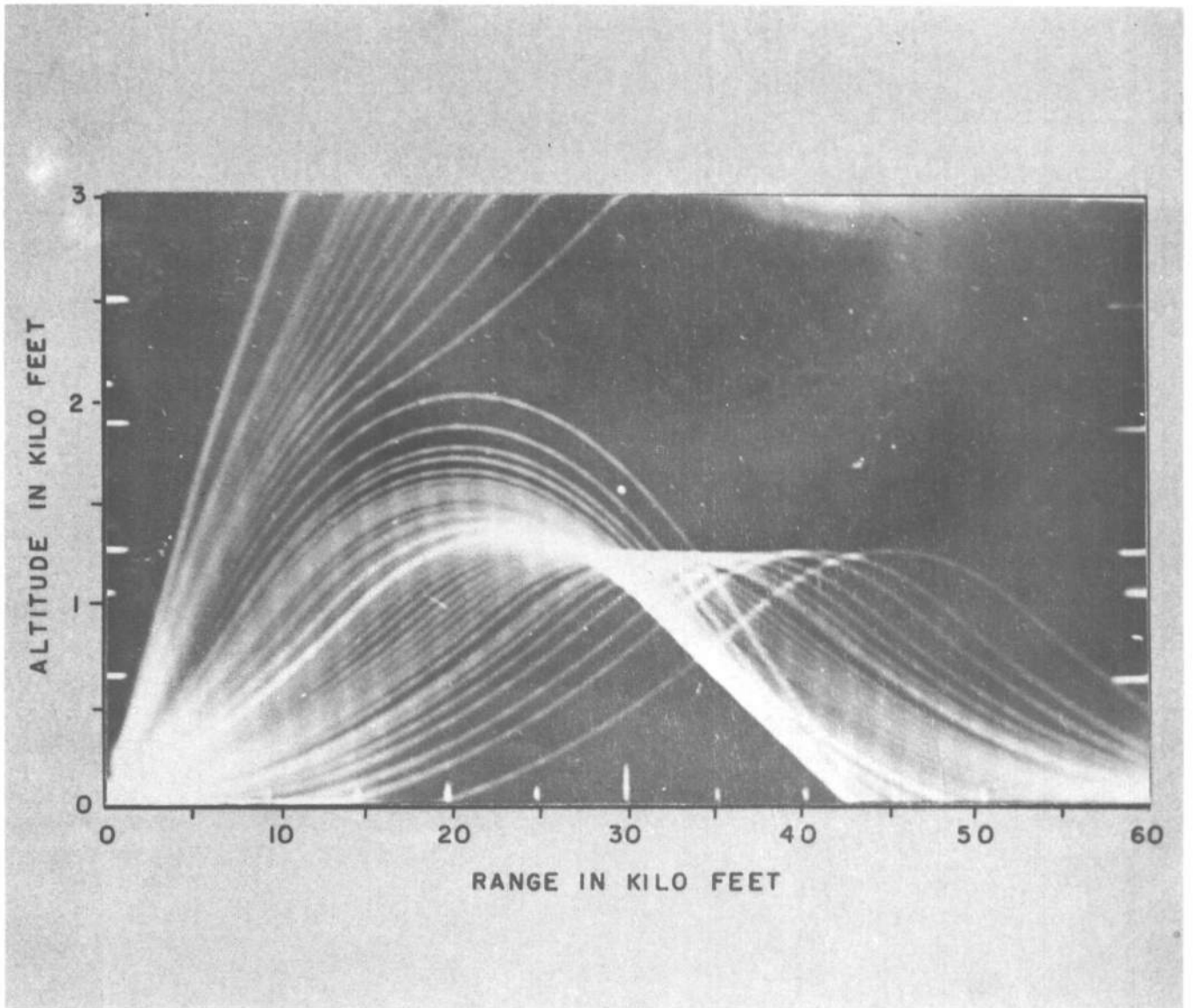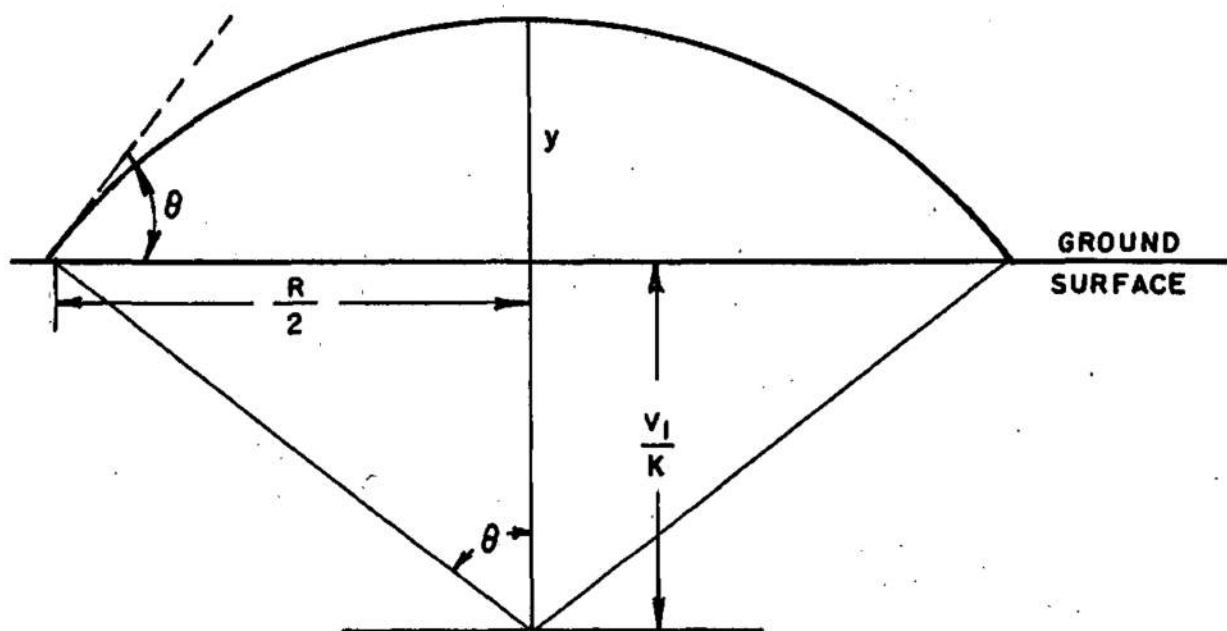
FIG. 3 - RAY PATHS CORRESPONDING TO GRADIENTS
REPRESENTED IN FIG. 2

θ = ANGLE OF DEPARTURE
R = HORIZONTAL RANGE
y = MAXIMUM ALTITUDE REACHED BY THE RAY.

FIGURE 4. - RANGE AND ALTITUDE FOR A GIVEN RAY IN
A MEDIUM OF A SINGLE GRADIENT

where V_1 = initial velocity and K is the velocity gradient.

The travel time $t = 2 \int_0^y \frac{ds}{V_y}$

in which $\qquad ds = \left[(dx)^2 + (dy)^2 \right]^{1/2}$

and $\qquad V_y = V_1 + Ky$

After integration:

$$t = \frac{2}{K} \log \cot \left(\frac{\pi}{4} - \frac{\theta}{2} \right)$$

For a medium having two gradients the path of a ray is pictured in Figure 5. The range of the ray departing at an angle θ_1 will be:

$$R = 2X_1 + 2 X_2$$

$$X_1 = a\,c - b\,c$$

$$ac = \frac{V_1}{K_1} \tan \theta_1$$

$$bc = \left(\frac{V_1}{K_1} + y_1 \right) \tan \theta_2$$

Since $V_2 - V_1 = K_1 Y_1$ then $y_1 = \frac{V_2}{K_1} - \frac{V_1}{K_1}$

and $X_1 = \frac{V_1}{K_1} \tan \theta_1 - \frac{V_2}{K_1} \tan \theta_2$

$$X_2 = \frac{V_2}{K_2} \tan \theta_2$$

and $R = \frac{2V_2}{K_2} \tan \theta_2 + \frac{2V_1}{K_1} \frac{\sin \theta_1}{\cos \theta_1} - \frac{2V_2}{K_1} \frac{\sin \theta_2}{\cos \theta_2}$
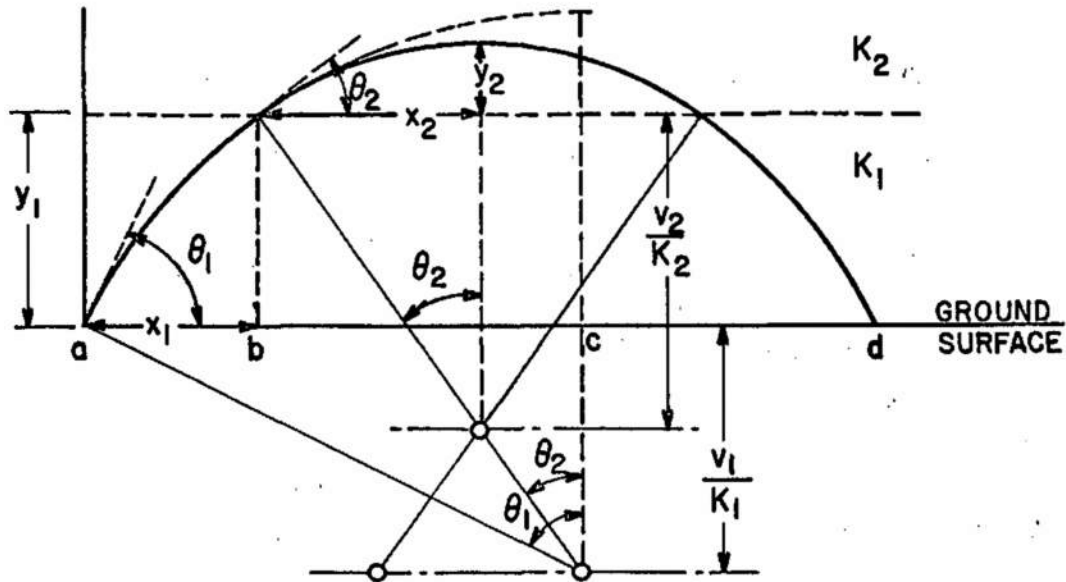
θ_1 = ANGLE BETWEEN RAY AND HORIZONTAL AT SURFACE.

θ_2 = ANGLE BETWEEN RAY AND HORIZONTAL AT TOP OF LAYER.

$a\,d$ = RANGE OF RAY = $2x_1 + 2x_2$

K_1, K_2 = GRADIENTS IN 1st AND 2nd LAYER RESPECTIVELY.

FIGURE 5 - RANGE OF RAY IN A MEDIUM OF TWO LAYERS
HAVING VELOCITY GRADIENTS OF K_1 & K_2

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which reduces to

$$R = \frac{2V_2}{K_2} \tan \theta_2 + \frac{2 V_1}{K_1 \cos \theta_1} (\sin \theta_1 - \sin \theta_2) \qquad (20)$$

The travel time for the two layered medium is

$$t = 2 \int_0^{y_1} \frac{ds}{V_y} \text{ (for 1st layer)} + 2 \int_{y_1}^{y_2} \frac{ds}{V_y} \text{ (for 2nd layer)}$$

For 1st layer

$$t_1 = 2 \int_0^{y_1} \frac{ds}{V_y} \text{ in which } ds = \left[(dx)^2 + (dy)^2 \right]^{1/2} \text{ and } V_y = V_1 + Ky$$

$$t_1 = 2 \int_0^{y_1} \frac{(\frac{1}{\sin \theta}) \, dy}{V_1 + Ky} = 2 \int_{\theta_1}^{\theta_2} \frac{- d\theta}{K_1 \cos \theta}$$

$$= - \frac{2}{K_1} \left. \log \tan \left(\frac{\pi}{4} + \frac{\theta_y}{2} \right) \right]_{\theta_1}^{\theta_2}$$

$$= \frac{2}{K_1} \left[\log \tan \left(\frac{\pi}{4} + \frac{\theta_1}{2} \right) - \log \tan \left(\frac{\pi}{4} + \frac{\theta_2}{2} \right) \right]$$

$$= \frac{2}{K_1} \left[\log \cot \left(\frac{\pi}{4} - \frac{\theta_1}{2} \right) - \log \cot \left(\frac{\pi}{4} - \frac{\theta_2}{2} \right) \right]$$

For 2nd layer

$$t_2 = 2 \int_{y_1}^{y_2} \frac{ds}{V_y} \text{ in which } V_y = V_2 + K_2 Y$$

$$= \frac{2}{K_2} \log \cot \left(\frac{\pi}{4} - \frac{\theta_2}{2} \right)$$

The total travel time $t = t_1 + t_2$

$$t = \frac{2}{K_1} \left[\log \cot \left(\frac{\pi}{4} - \frac{\theta_1}{2} \right) - \log \cot \left(\frac{\pi}{4} - \frac{\theta_2}{2} \right) \right]$$

$$+ \frac{2}{K_2} \log \cot \left(\frac{\pi}{4} - \frac{\theta_2}{2} \right) \tag{21}$$

The symbols of equation (21) are defined in the diagram of Figure 6.

Figure 7 presents a plot of the travel time (t) versus angle of departure (θ) and range (R) versus θ for the case of transmission through an atmosphere in which two velocity gradients K_1 and K_2 exist, K_1 being less than K_2. It should be noted that at $\theta = \theta_1$ the travel time curve and the range pass thru a minimum. Furthermore, both the travel time and range change very slowly with θ in the vicinity of θ_1. This indicates that for the conditions stated for Figure 7, a cone of rays will be converged at a range of R_1 with very slight differences in phase which will produce an increase in intensity. The various combinations of gradients that will produce this focussing is of vital interest and can best be shown by calculating ray paths for various combinations of gradients that can be expected to occur. An analogue computer has been used to calculate and trace ray paths for single gradients and for combinations of two to seven gradients. The solutions show paths for a group of rays starting at different angles of departure. If focussing occurs the convergence will be shown as well as the distance to the point of focus.

The Piedmont Division of Sperry-Rand Corporation, Charlottesville, Virginia, designed the analogue computer used. With it the effect of from one to twenty gradients can be considered. The computer is small in volume (about two cubic feet) and provides the solution in a few minutes. In order to simplify the construction of the computer some simplifying assumptions were made in the solution of the equation of the ray path. The approximations and the resulting errors are insignificant. This is demonstrated in Appendix A.
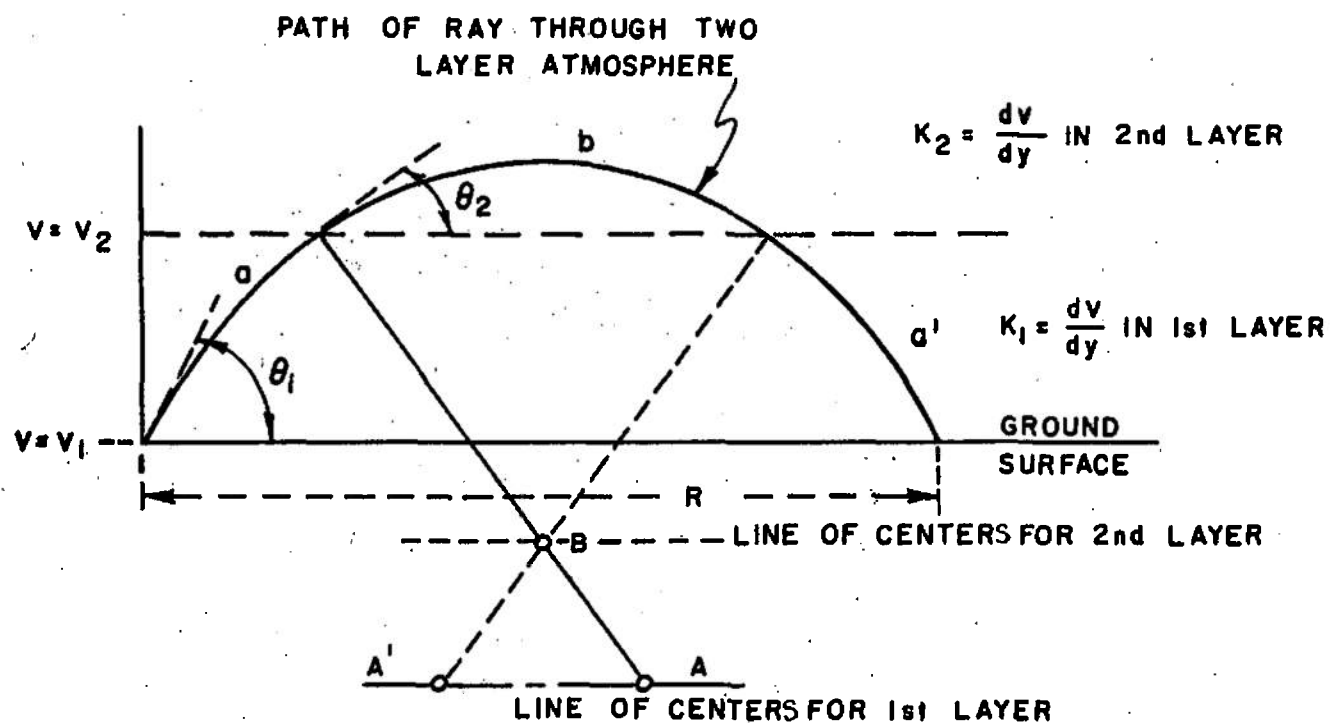
PATH OF RAY THROUGH TWO LAYER ATMOSPHERE

$K_2 = \dfrac{dv}{dy}$ IN 2nd LAYER

$K_1 = \dfrac{dv}{dy}$ IN 1st LAYER

$V = V_2$

$V = V_1$

θ_2

θ_1

a

b

a'

GROUND SURFACE

R

B — LINE OF CENTERS FOR 2nd LAYER

A'

A

LINE OF CENTERS FOR 1st LAYER
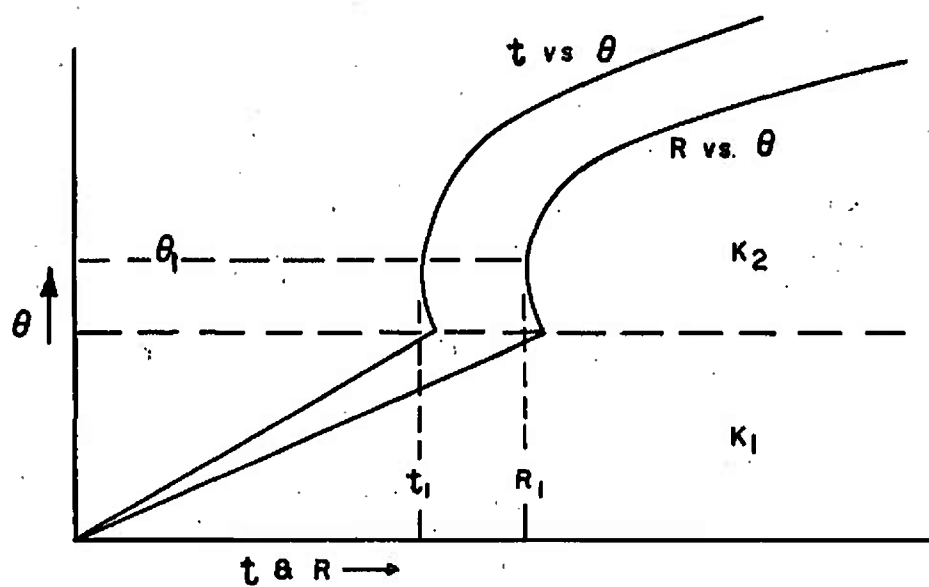
FIG 6 —DIAGRAM DEFINING TERMS IN EQUATION 21

FIG. 7 - PLOT OF TRAVEL TIME AND RANGE vs.
ANGLE OF DEPARTURE θ

BLAST WAVE INTENSITY

The overpressure in a blast wave when propagated through an atmosphere in which the velocity gradient is zero has been determined for various distances for several different weights of explosive. At a given distance the overpressure in the blast wave will be different if the explosive is detonated at the surface of the ground or in free air. The measured value will also be different if the pressure gage is at the surface of the ground or in free air. In Figure 8 graphs are shown which give the overpressure versus distance for several weights of explosive detonated at the surface and the overpressure measured at the surface for a uniform atmosphere.

When the ray paths of sound are affected by gradients in the atmosphere the intensity at a given distance will be some multiple of the overpressure given in Figure 8 for the given distance. The combinations of gradients to be experienced can be classed as one of five basic types or categories. The types are shown in Figure 9. For each type approximate values have been determined for a "multiplication factor" to calculate the intensity at a focus due to that type of gradient combination.

The value of intensity at a focus compared to the intensity at the same distance in a uniform atmosphere has been derived from the experience of several years. A few direct and many indirect determinations have been made. By noting the distance to a particular type of damage and assuming the minimum overpressure known to produce such damage, a maximum "multiplication factor" can be calculated. Such indirect methods have provided conservative but very useful values for calculating overpressures to be expected. The calculation of the intensity to be expected at the focus is made as follows:

The distance from the explosion to the focus is noted in the solution on the computer, and the intensity of the blast wave at that distance in a uniform atmosphere is read from Figure 8. The category of the gradient combinations in the atmosphere is determined by comparison of the velocity versus altitude curve with Figure 9 and the
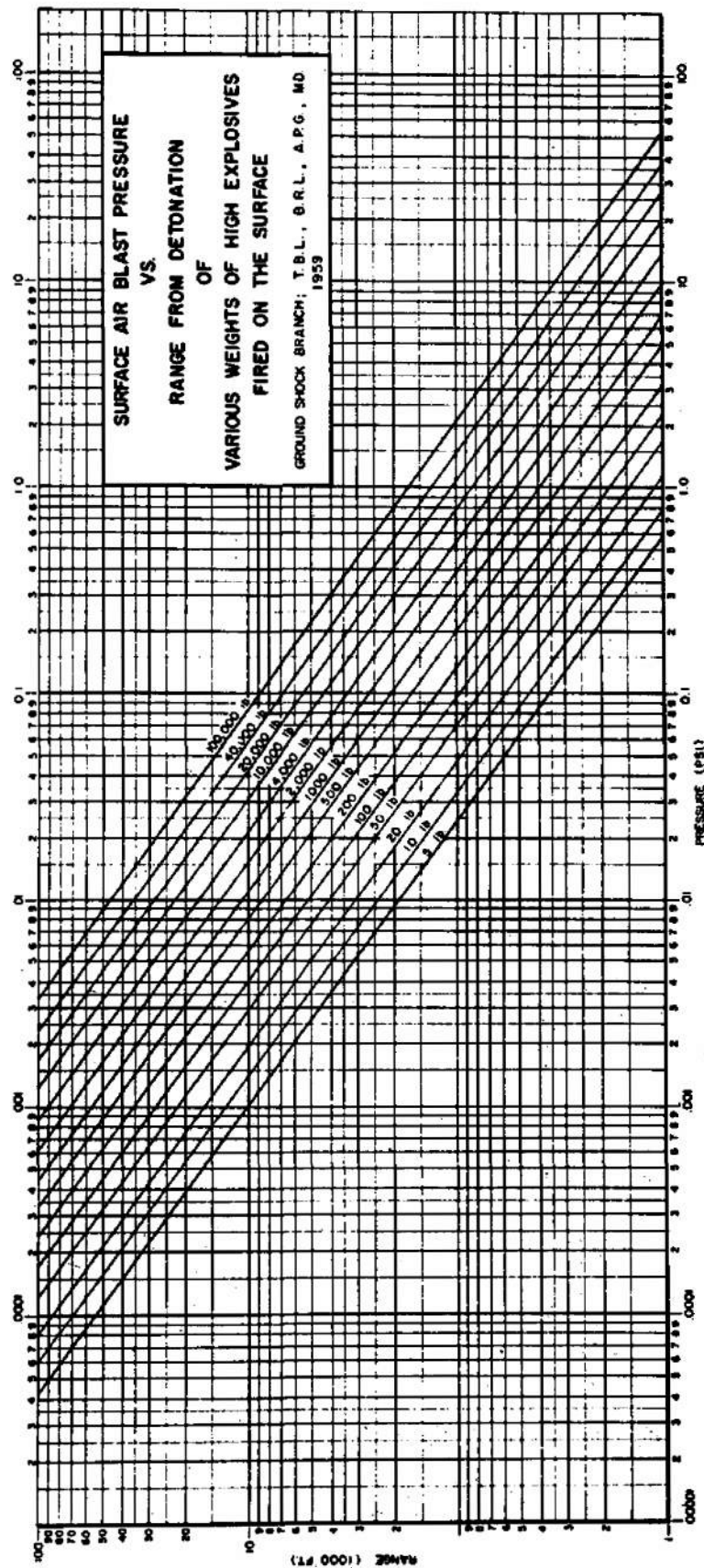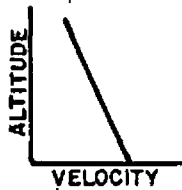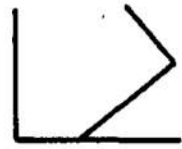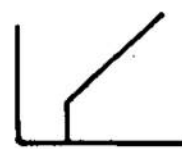
SURFACE AIR BLAST PRESSURE
VS.
RANGE FROM DETONATION
OF
VARIOUS WEIGHTS OF HIGH EXPLOSIVES
FIRED ON THE SURFACE

GROUND SHOCK BRANCH; T.B.L., B.R.L., A.P.G., MD
1959

FIG. 8

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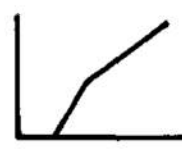
CATEGORY	DESCRIPTION		MULTIPLICATION FACTOR
1	SINGLE NEGATIVE GRADIENT		0
2	SINGLE POSITIVE GRADIENT		5
3	ZERO GRADIENT NEAR SURFACE WITH POSITIVE GRADIENT ABOVE		10
4	WEAK POSITIVE GRADIENT NEAR SURFACE WITH STRONG POSITIVE GRADIENT ABOVE		25
5	NEGATIVE GRADIENT NEAR SURFACE WITH STRONG POSITIVE GRADIENT ABOVE		100

FIG. 9 — VARIOUS TYPES OF VELOCITY GRADIENTS TO BE EXPECTED AND THE INCREASE IN INTENSITY AT A FOCUS FOR EACH TYPE.

"multiplication factor" is observed. The intensity read from Figure 8 multiplied by the "multiplication factor" will be the intensity at the focus to be expected.

DAMAGE CAUSED BY BLAST WAVES

The damage caused by the overpressure of a blast wave depends to a very large extent on the type of construction. Glass panes of average size and thickness vary greatly in their ability to withstand blasts depending on how the panes are mounted. If the pane is forced into the frame so as to be under a constant strain, a blast wave of 0.1 psi overpressure can cause the pane to crack but if it is mounted without any strain in the glass an overpressure of about 0.75 psi may be required to crack it.

The cracking of plaster on a wall depends on the flexibility of the wall. A plastered surface attached to a masonry wall will withstand a much higher pressure than a surface supported by a wide wooden panel. In general a well constructed plastered wall will stand higher over-pressures than average window panes.

An overpressure of .03 to .05 psi in a blast wave can cause a loose window sash to slap the window frame and produce a loud noise while actually no damage is being done. In contrast to this, the quiet settling of one corner of a house can cause damage to walls and windows which is often attributed to blast waves.

GATHERING METEOROLOGICAL DATA

The meteorological data are gathered by release of a weather balloon and radiosonde. A GMD 1 A Rawin set is used at Aberdeen Proving Ground. The wind data are calculated from the successive positions of the balloon which is determined at frequent intervals. The air temperature is telemetered back by the radiosonde. From the ground surface to 5000 feet altitude, the temperature and wind velocity and direction should be determined for 500 feet intervals. From 5000 feet to about 12000 feet the data should be determined every 1000 feet. The data are recorded as in the sample data sheet (Figure 10). The air temperature is recorded in degrees centigrade. A change in temperature

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APG   RELEASE TIME __1243 HRS.__   DATE __13 NOV. 1959__

AZIMUTH OF INTEREST __206°__

1	2	3	4	5	6	7	8	9	10
AIR TEMP. °C	ALTITUDE ABOVE SURFACE (FEET)	WIND DIRECTION FROM TRUE NORTH (DEGREES)	ANGLE WITH AZIMUTH $\gamma°$ (DEGREES)	COS γ	WIND VELOCITY		COMP OF WIND FT/SEC	ΔV DUE TO TEMP FT/SEC	TOTAL CHANGE VELOCITY FT/SEC
					MI/HR	FT/SEC			
15.1	0	030	86	.07	5	7.3	−1	30	29
12.0	720	102	14	.97	7	11	−10	24	14
11.5	1200	162	44	.72	11	16	11	23	34
11.0	1790	193	13	.97	14	21	20	22	42
9.5	2320	201	5	.99	14	21	20	19	39
9.5	2910	194	12	.98	17	25	24	19	43
8.2	3440	201	4	.99	19	28	28	16	44
6.9	4520	216	10	.98	22	32	32	14	46
5.2	5600	216	10	.98	23	34	33	10	43
3.0	6680	210	4	.99	25	37	36	6	42
1.3	7820	208	2	.99	24	35	35	3	38
0.9	8850	220	14	.97	22	32	31	2	33
0.2	9700	231	25	.90	27	40	36	0	36
−1.4	10750	235	29	.87	30	44	39	−3	36

NOTE:
    IN COLUMN 3 − RECORD DIRECTION TO WHICH WIND IS BLOWING
    IN COLUMN 4 − ANGLE BETWEEN WIND DIRECTION AND AZIMUTH OF INTEREST
    IN COLUMN 8 − (WIND VELOCITY AT EACH ALTITUDE) x (COS γ AT SAME ALTITUDE)
    IN COLUMN 9 − (VALUE IN COLUMN 1 AT EACH ALTITUDE) x 2
    COLUMN 10 IS THE SUM OF COLUMNS 8 AND 9

FIGURE 10 − SAMPLE DATA SHEET

of the air of $1^{\circ}C$ changes the velocity of sound almost exactly 2 feet/ second, so the difference between the velocity of sound at a given temperature and the velocity at $0^{\circ}C$ is determined by multiplying the temperature by 2. Since the effect of wind varies with direction, the component of the wind in the direction of interest must be calculated for each elevation.

At each elevation, the sum of the component of the wind in the direction of interest (column 8 in Figure 10) and the change in velocity due to the temperature (column 9) will give the difference between the velocity at that elevation and the velocity at zero degrees centigrade. If the values of this resultant (column 10) are plotted on linear co- ordinates as in Figure 11, the variation in velocity is depicted and the magnitude of the gradients can be measured. Figure 11, is the presentation of the data upon which the forecast of a focus and its location is based. If the wind varies widely in direction with altitude, it may be necessary to reduce the data for two or more directions, each case being treated separately as described above.

FORECASTING THE FOCUS

If the velocity data shown in Figure 11 are furnished to the Sperry-Rand analogue computer, a presentation of the resulting ray paths will be shown on the screen. Ray paths corresponding to the conditions depicted in Figure 11 are shown in Figure 12. If a focus occurs, it will be seen on the screen where the rays converge and the distance from the source will be shown.

Actually at APG, it has been found that the pattern of gradients often repeat so that a library of 32 "typical gradients" and the resulting ray paths have been accumulated. Generally the gradients recorded daily can be matched sufficiently close with one of the "typical gradients" to be used for a forecast. The computer should be kept at hand for more precise determination when needed and for those cases for which there is no matching typical gradient. The typical gradients are included in Appendix B.
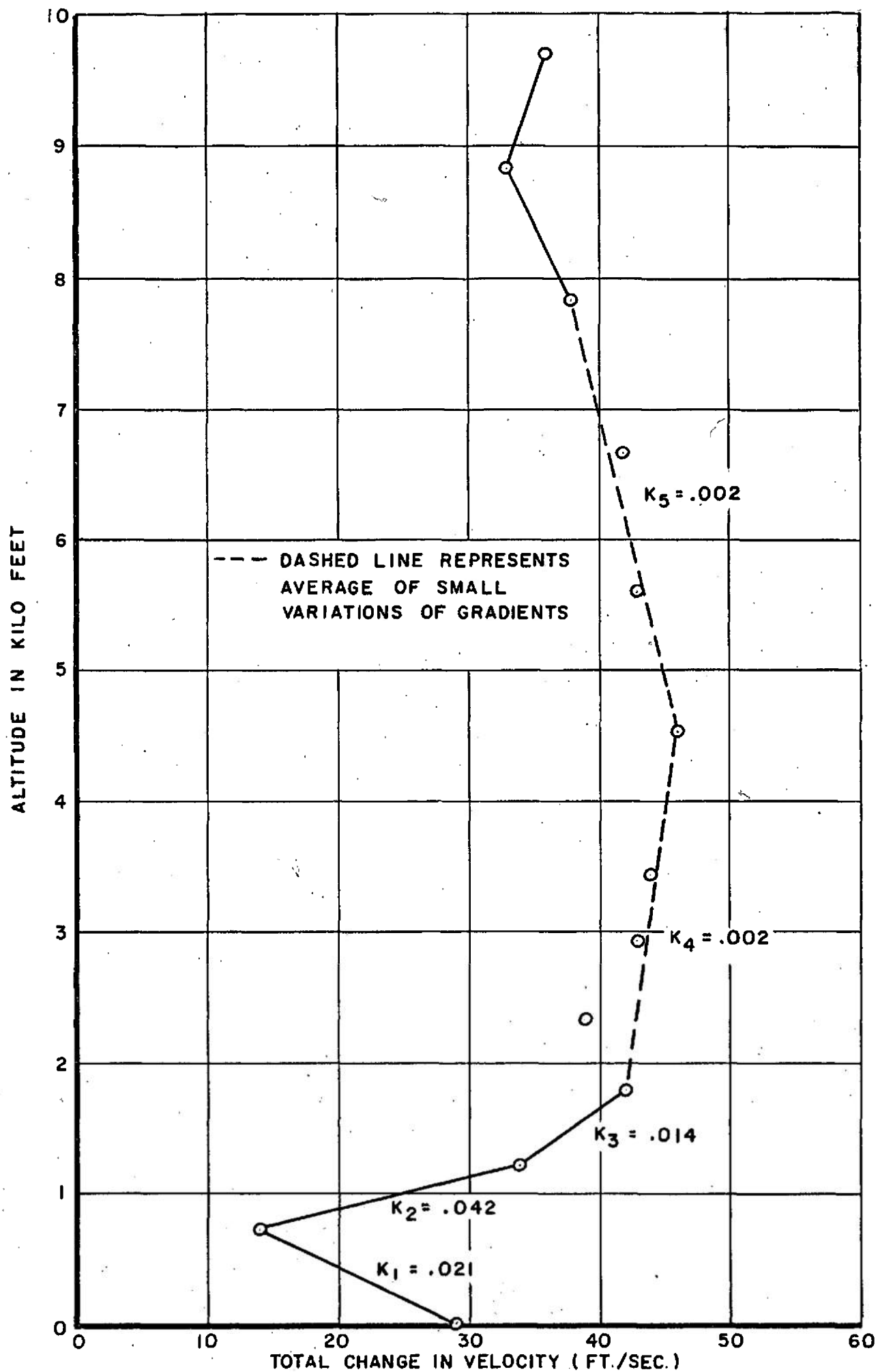
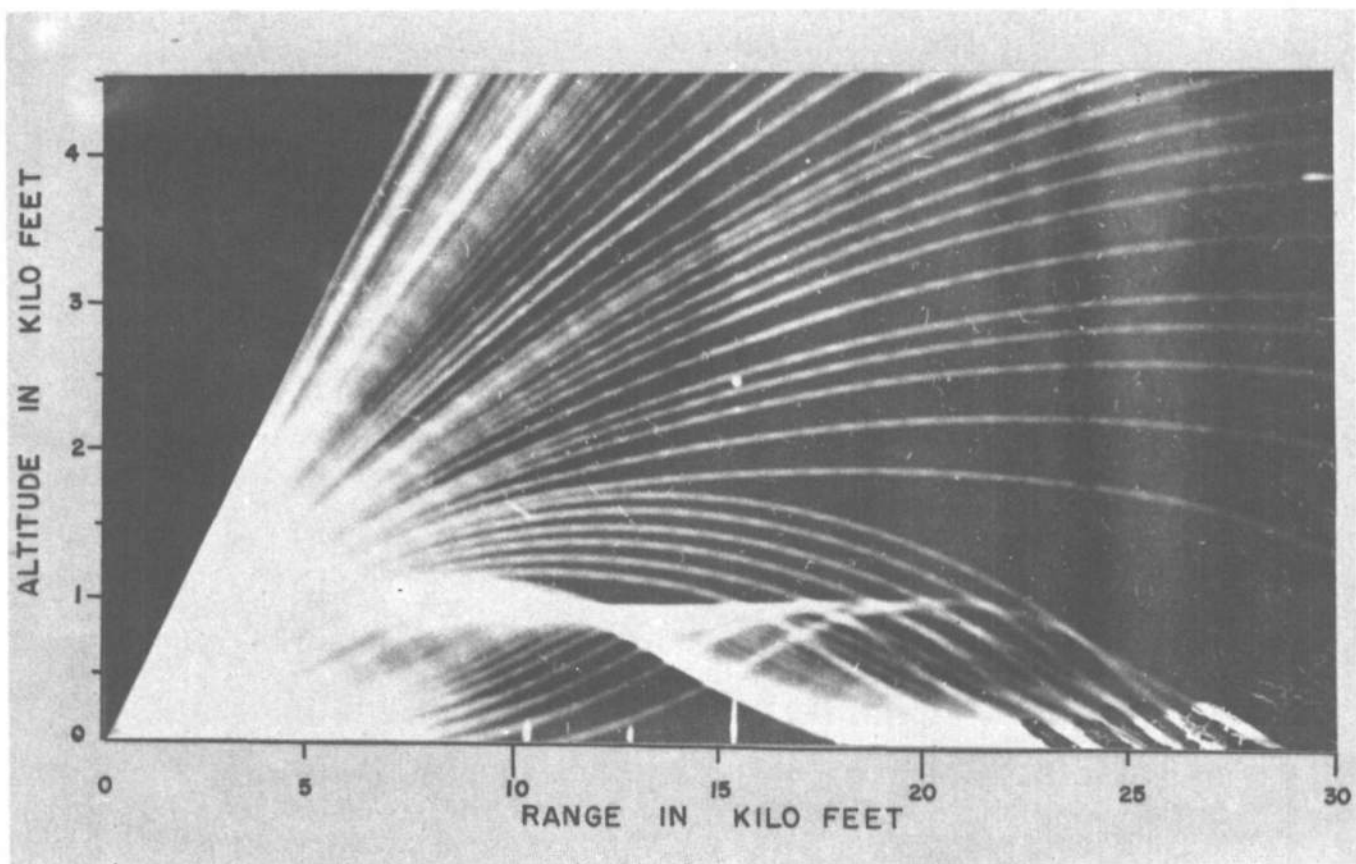FIG II-PLOT OF TOTAL CHANGE IN VELOCITY vs. ALTITUDE

FIG. 12 – RAY PATHS CORRESPONDING TO GRADIENTS
REPRESENTED IN FIG. II

COMMENTS AND RECOMMENDATIONS

When a government establishment is put in an isolated area, the regions just beyond the exits may soon be occupied by non-government employees desiring to supply goods or services and the area may become a site for housing developments.

If possible, a test center involving the use of explosives should be so located that the prevailing upper winds will blow from the source of blast waves toward a wide stretch of Government owned lands or to the open sea.

The entrances to the establishment should be so located that the prevailing upper winds will blow from them toward the point of detonation.

The direction of the winds are determined by the position of the high and low pressure areas in the atmosphere and with a little experience in this procedure a study of the daily weather maps will permit a meteorologist to forecast good shooting periods several days in advance. Since the conditions in the atmosphere usually drift toward the east, the preceding statement will be of no help to stations along the Pacific Coast because no detailed data for the area immediately west of the coast is given on the weather maps.

The most desirable time for detonating an explosive is when the center of a high pressure area is at the point of detonation. The temperature of the air around the test site will then be found to decrease with altitude and the wind will be at a minimum. Under such conditions, the blast waves are refracted upward and the detonation of a large charge (1000 pounds of TNT) would be barely audible at a distance of one or two miles.

Generally the weather conditions change slowly, since the areas of high and low atmospheric pressures are large and on the average move only 300 miles per day. Therefore the conditions indicated by the meteorological data can be expected to remain sufficiently constant for about 8 hours. The firing should be started as soon as possible after the meteorological data are taken. If the firing is to extend from daylight

31

conditions into the night, it is advisable to make a "metro" run in the late afternoon to detect any changes that are occurring. If the weather map shows a "weather front" to be approaching caution in the firing is advisable. Firing should be discontinued during the passing of the "front" and a metro run should be made after the passage of the "front" to determine if firing can be resumed.

It should be noted that the worst focusing conditions can cause the pressures indicated in Figure 8 to be multiplied by 100. If the weight of the explosive being detonated is so small that the pressure at the nearest point of possible damage could not exceed 0.1 psi even under the worst conditions, then firing can proceed without a metro run. This procedure will sometimes cause complaints of annoyance but should not result in damage.

<div align="center">RECAPITULATION</div>

The following summary of the Standard Operating Procedure will serve as a convenient guide:

1. The meteorological balloon should be released 2 or 3 hours before the firing program is scheduled to begin.

2. The wind and temperature data should be reduced and tabulated as in Figure 10. Data should be recorded at intervals of 500 feet from the surface to 5000 feet altitude and at intervals of 1000 feet from 5000 feet to 12000 feet altitude.

3. The velocity versus altitude should be plotted for each azimuth of interest as in Figure 9 and the velocity gradients should be noted.

4. The combination of gradients for each azimuth should be compared to the set of 32 in Appendix B and the location of the focus (if one is indicated) should be noted.

(If no sample velocity versus altitude curve in Appendix B can be found to match the one just plotted then the analogue computer must be used.)

5. With the weight of explosives to be detonated and the distance to the focus known, the pressure to be expected in a uniform atmosphere

<div align="center">32</div>

can be read from the chart on Figure 8 of the text.

6. By comparing the velocity versus altitude curve to the five basic types shown in Figure 9, the multiplication factor for the prevailing conditions can be determined.

7. If the pressure read from Figure 8, multiplied by the multiplication factor determined from Figure 9, is 0.1 psi or greater, firing should be postponed.

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PAUL H. LORRAIN

WILLIAM H. TOWNSEND

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APPENDIX A

APPROXIMATIONS IN ANALOGUE

SOLUTION OF RAY PATHS

The following was furnished by Mr. DeBow Owen of Piedmont Division, Sperry-Rand Corporation, Charlottsville, Virginia.

Since the Ray Tracer computing system integrates in the time domain, y must be expressed as a function of time;

$$\dot{y} = \frac{dy}{dt} = \frac{dy}{ds}\frac{ds}{dt} = V_y \sin \theta_y \qquad (1)$$

in which θ_y = angle between the ray and the horizontal and V_y is the velocity of sound, at altitude Y.
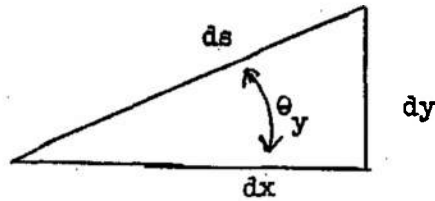
$$\ddot{y} = \frac{d}{dt} (V_y \sin \theta_y)$$

$$= \frac{1}{C} (\cos^2 \theta_y - \sin^2 \theta_y) \frac{d\theta_y}{dt}$$

$$= \frac{1}{C} (\cos 2\theta_y) \frac{d\theta_y}{dt} \qquad (2)$$

Since $\cos \theta_y = CV_y$, $\frac{d\theta_y}{dt} = -CV_y \frac{dV_y}{dy}$

and substituting in (2)

$$\ddot{y} = -V_y (\cos 2\theta_y) \frac{dV_y}{dy} \qquad (3)$$

In the Ray Tracer the assumption is made that the horizontal distance traveled is equal to a constant average velocity times the travel time,

i.e., $x = V_{av} t$, $\qquad V_{av}$ = constant

then $\dot{y} = \dfrac{dy}{dx}\ \dfrac{dx}{dt} = V_{av}\ \tan \Theta_y$ $\qquad$ (4)

and $\ddot{y} = V_{av}\ \sec^2\Theta_y\ \dfrac{d\Theta_y}{dt}$ $\qquad$ (5)

Now $\qquad\qquad \Theta_y = \cos^{-1}\ (C)\ (V_y)$

$\qquad$ and $\qquad \dfrac{d\Theta_y}{dt} = -\ \dfrac{C}{\sin \Theta_y}\ \dfrac{dV_y}{dt}$

$\qquad\qquad\qquad\qquad = \dfrac{-C}{\sin \Theta_y}\ \dfrac{dV_y}{dy}\ \dfrac{dy}{dx}\ \dfrac{dx}{dt}$

$\qquad\qquad\qquad\qquad = \dfrac{-C}{\sin \Theta_y}\ (\tan \Theta_y)\ (V_{av})\ \dfrac{dV_y}{dy}$

$\qquad\qquad\qquad\qquad = \dfrac{-C\ V_{av}}{\cos \Theta_y}\ \dfrac{dV_y}{dy}$

and $\qquad \ddot{y} = \dfrac{-C\ V^2_{av}}{\cos \Theta_y}\ \sec^2 \Theta_y\ \dfrac{dV_y}{dy}$ $\qquad$ (6)

and again since $\qquad \dfrac{C}{\cos \Theta_y} = \dfrac{1}{V_y}$

$\qquad\qquad\qquad \ddot{y} = \dfrac{-V^2_{av}}{V_y \cos^2 \Theta_y}\ \dfrac{dV_y}{dy}$ $\qquad$ (7)

The gradients commonly experienced in the lower atmosphere are small (0 to .040 ft/sec/ft.) and persist for only a few thousand feet. For this reason, the rays that return to the surface will traverse a path, the direction of which will have a maximum inclination to the horizontal less than 12 degrees. Therefore a further approximation has been made that $\cos^2 \Theta_y = 1$.

Then $\ddot{y} = \dfrac{-V^2_{av}}{V_y}\ \dfrac{dV_y}{dy}$ $\qquad$ (8)

Equation (8) is used in the ray tracer in lieu of the more precise equation (21) of the text. A comparison of the exact solution of these two equations will provide an estimate of the error caused by the approximations. When the initial slope of the ray is eleven degrees, the difference between the true and the approximate maximum height reached by the ray is 1.6 per cent. The difference in the true range and the approximate range is 1.2 per cent. These differences are insignificant.

APPENDIX B

TYPICAL VERTICAL VELOCITY GRADIENTS

In the following pages there is presented a set of gradients which are typical of conditions found at Aberdeen Proving Ground over a two year period. The velocity at each altitude was determined from the temperature and wind velocity.

With each velocity versus altitude curve the resulting sound ray paths, as computed on the Sperry-Rand Electronic Ray Plotter, are shown.

ALTITUDE IN KILO-FEET

RANGE IN KILO-FEET

K = −.007

K = −.004

K = −.005

K = FT./SEC./FT.

K = −.010

ALTITUDE (KILO-FT.)

VELOCITY (FT./SEC.)

FIGURE 1

14

FIGURE 2

ALTITUDE IN KILO-FEET

RANGE IN KILO-FEET

K = −0.006

K = FT./SEC./FT.

K = +0.010

ALTITUDE (KILO-FEET)
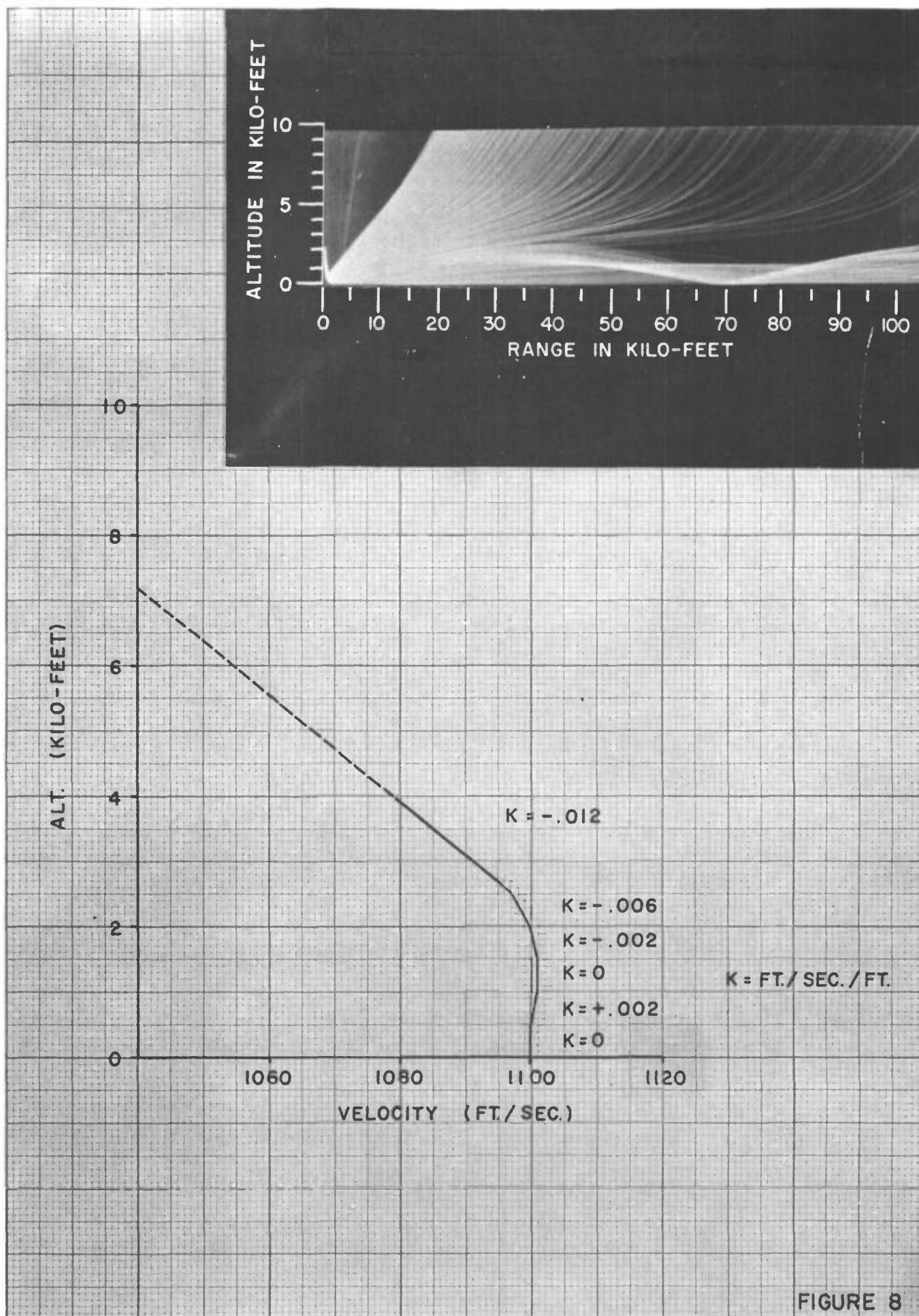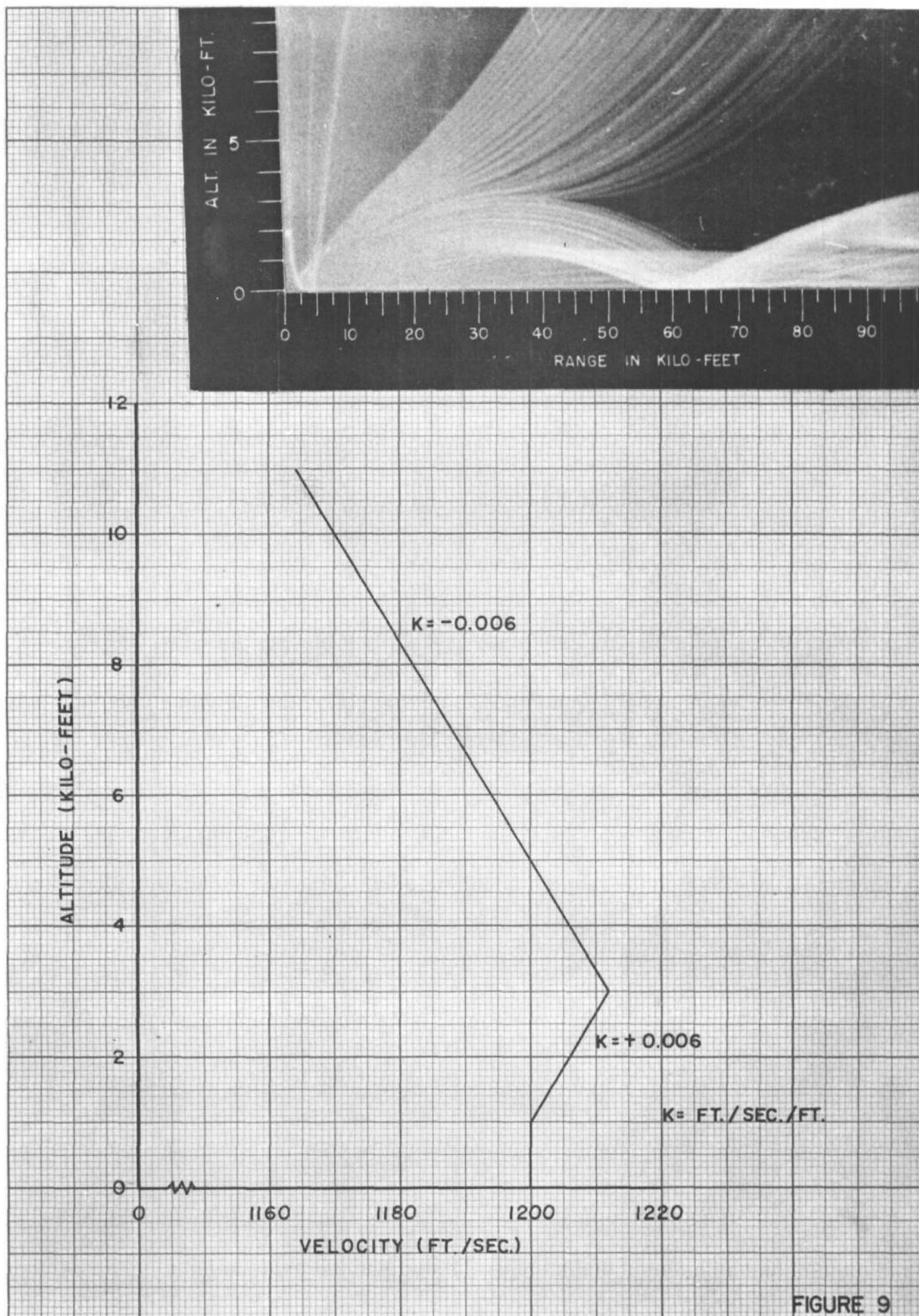
VELOCITY (FT./SEC.)

FIGURE 3

43
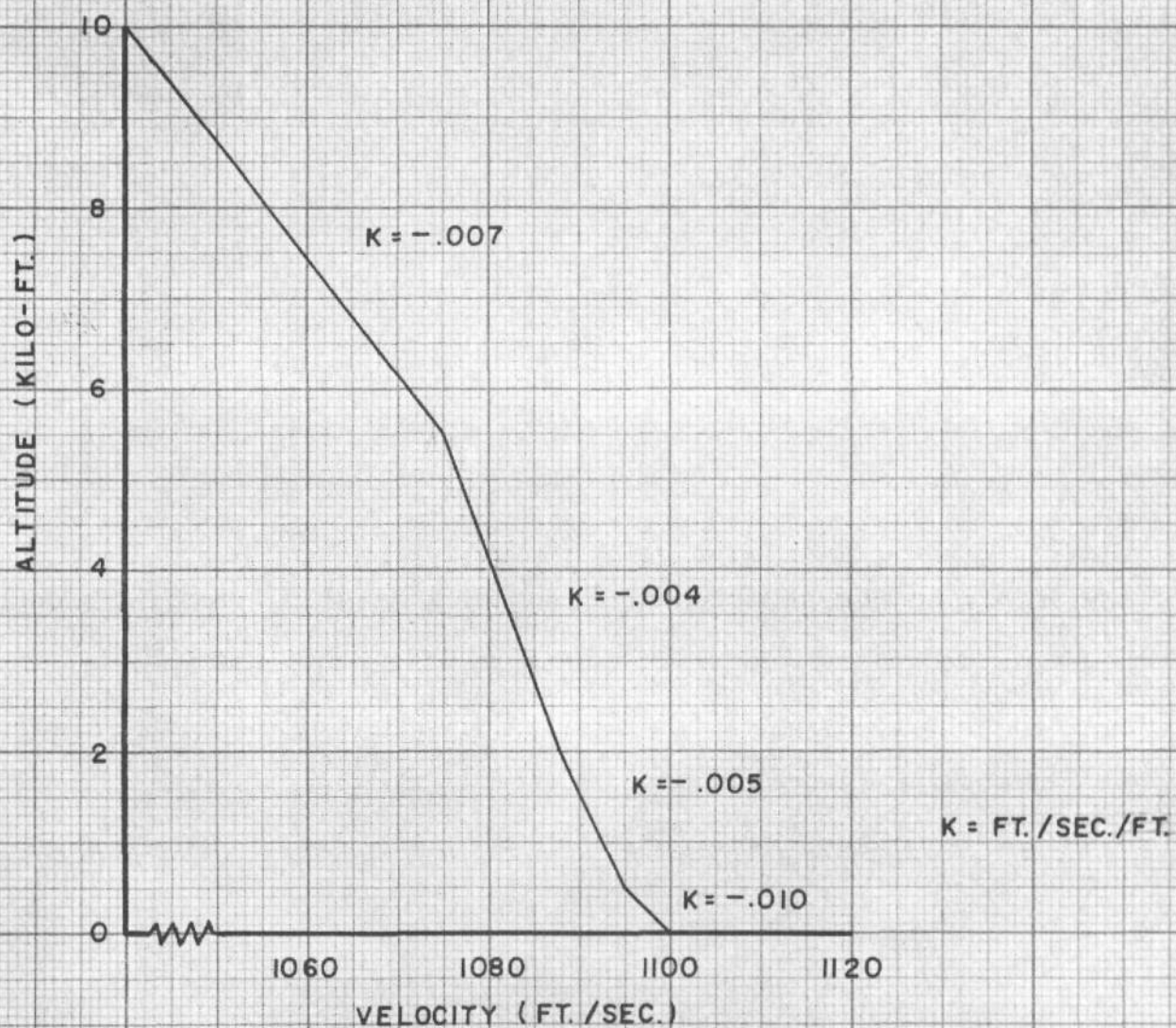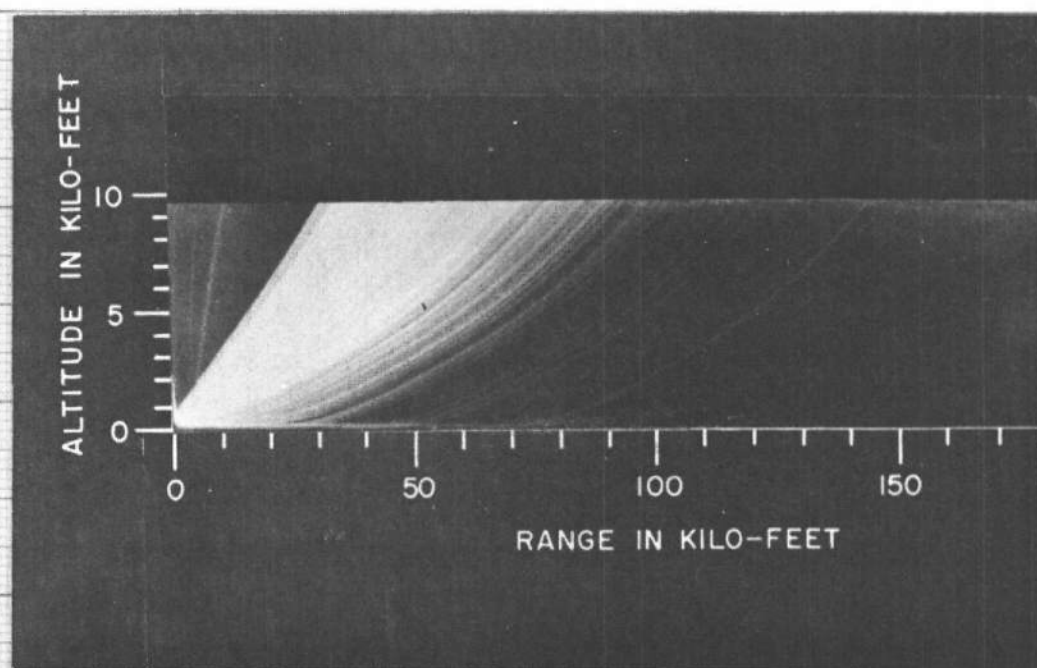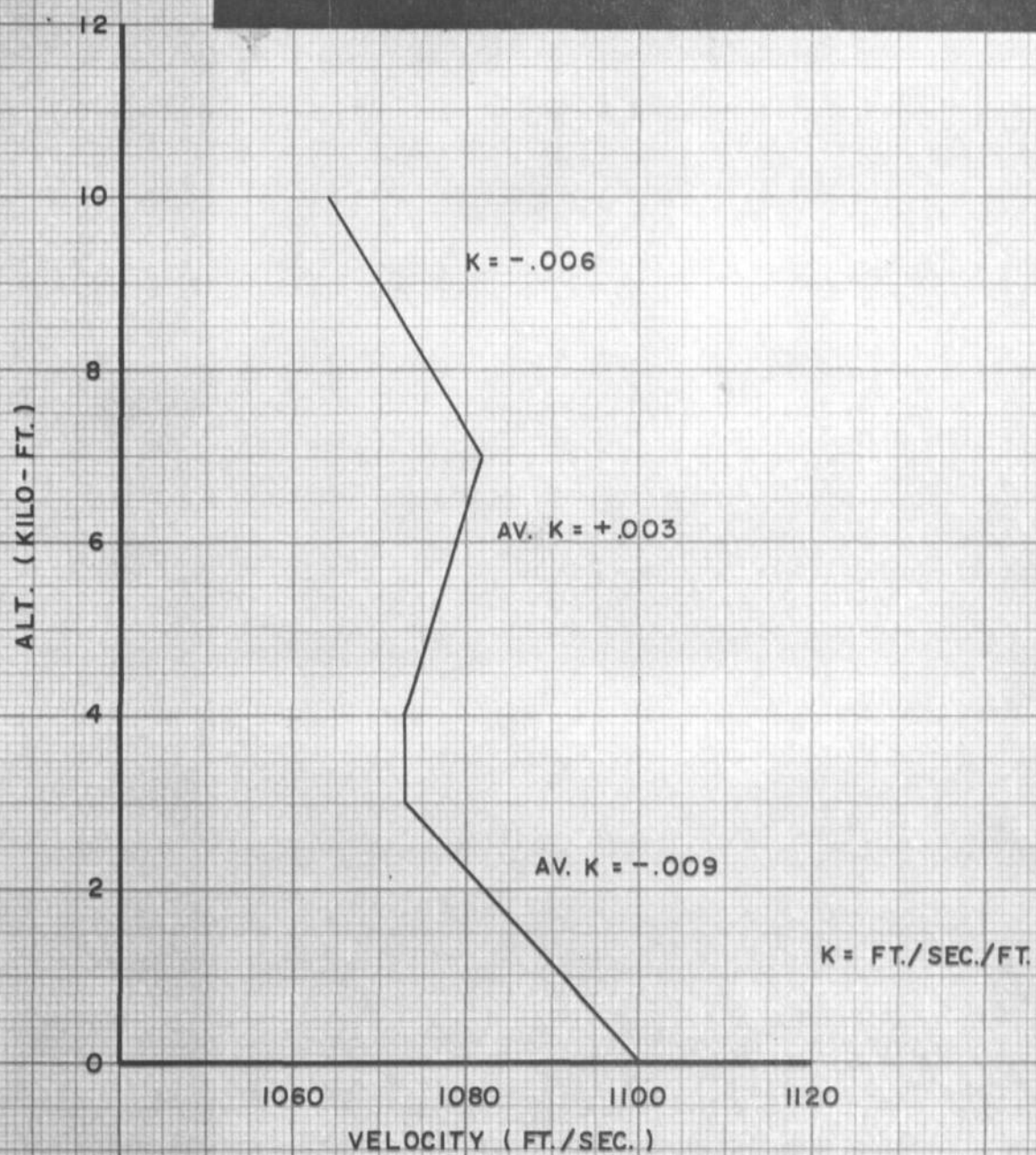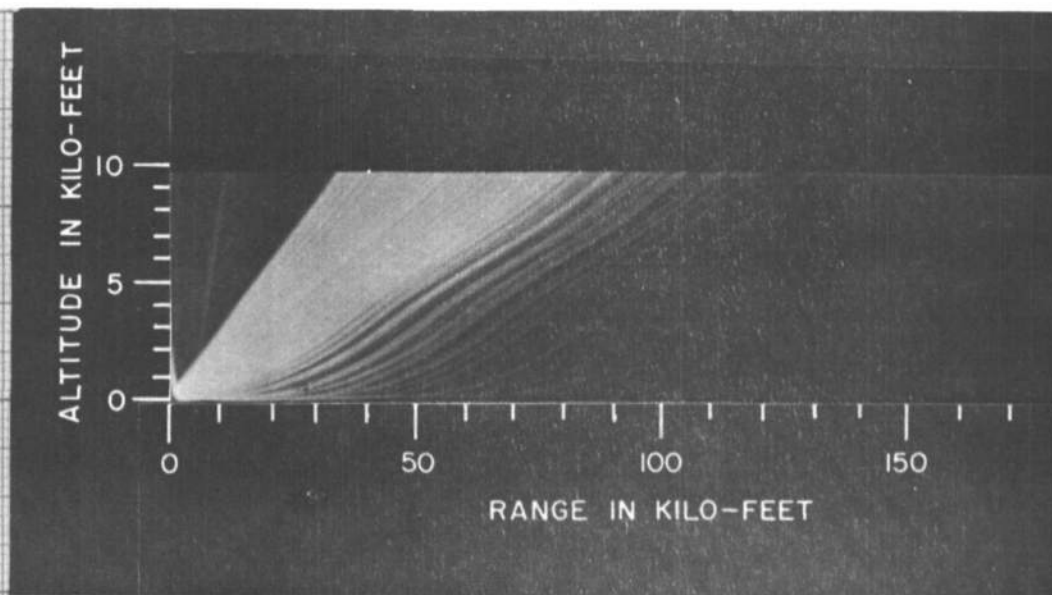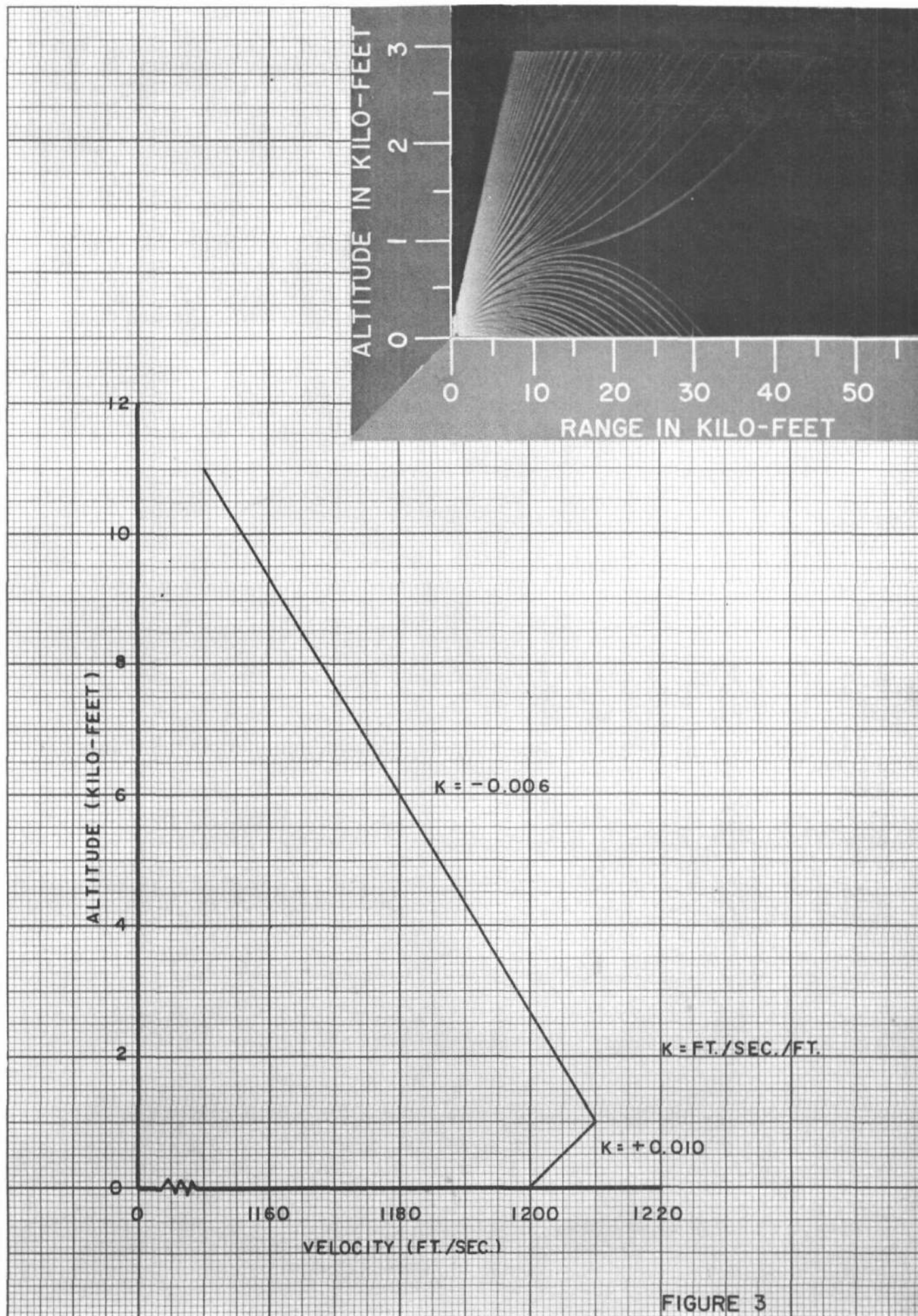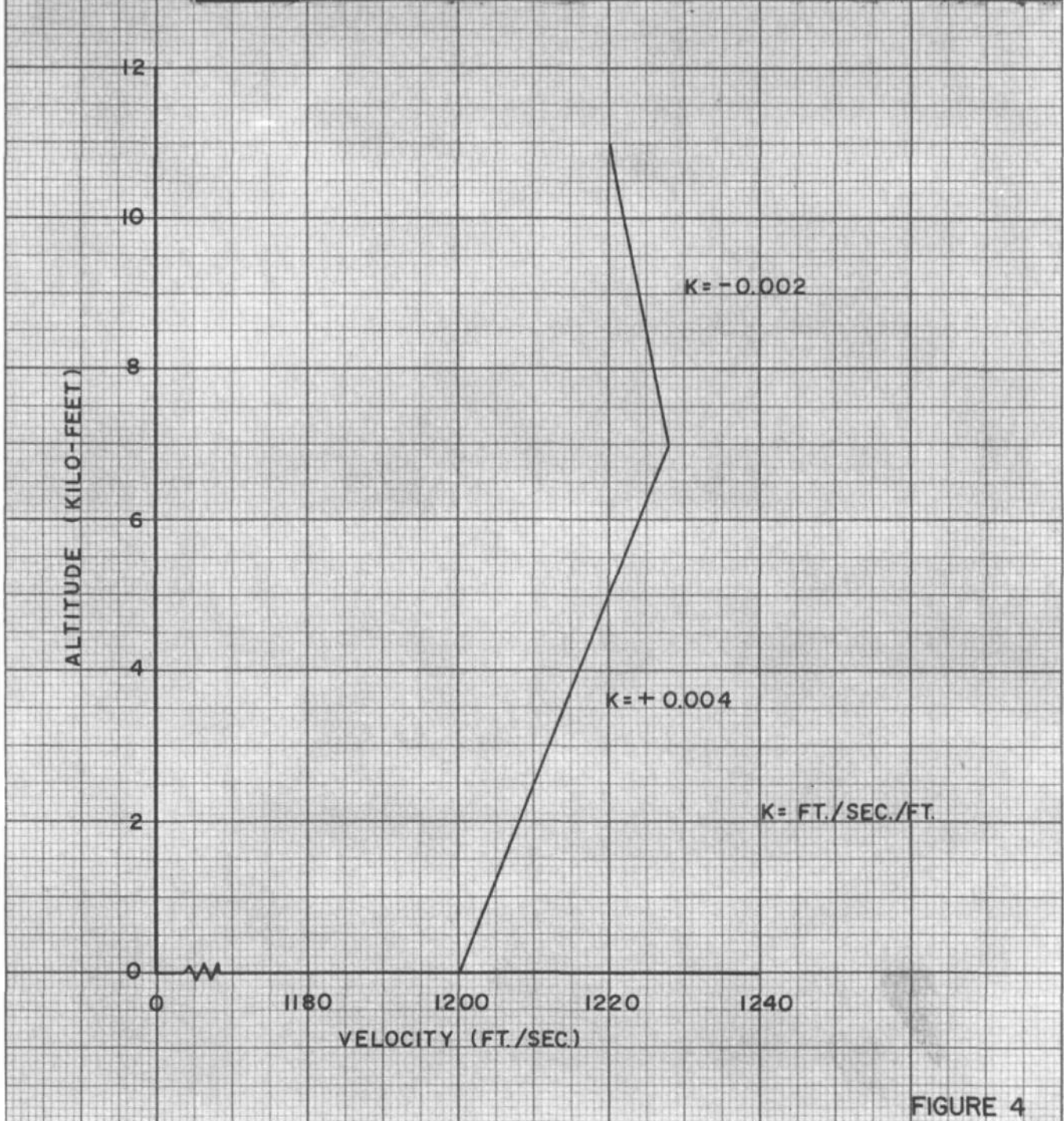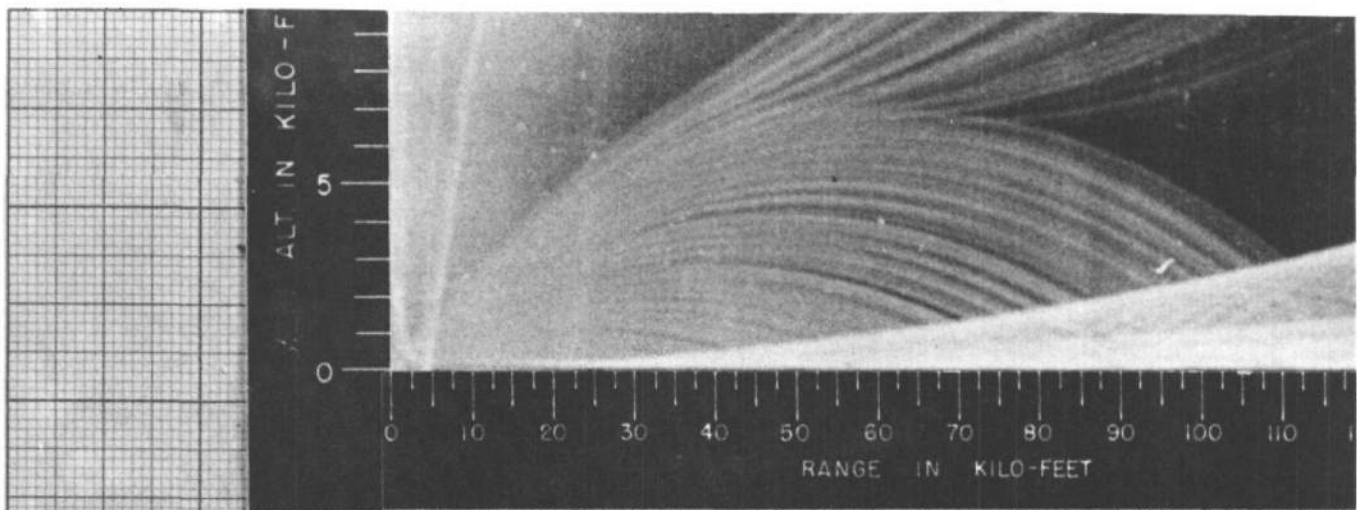
FIGURE 4

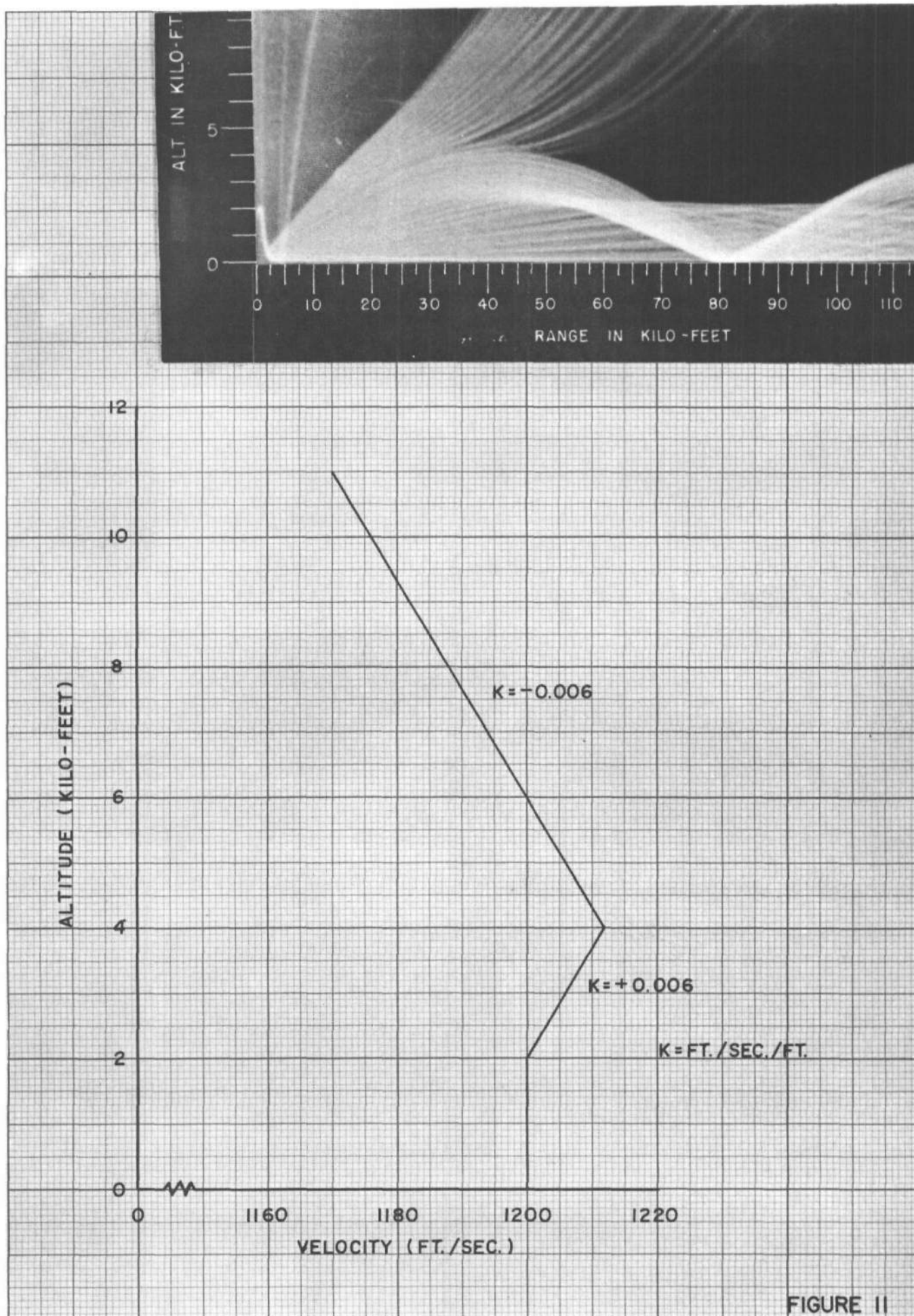44
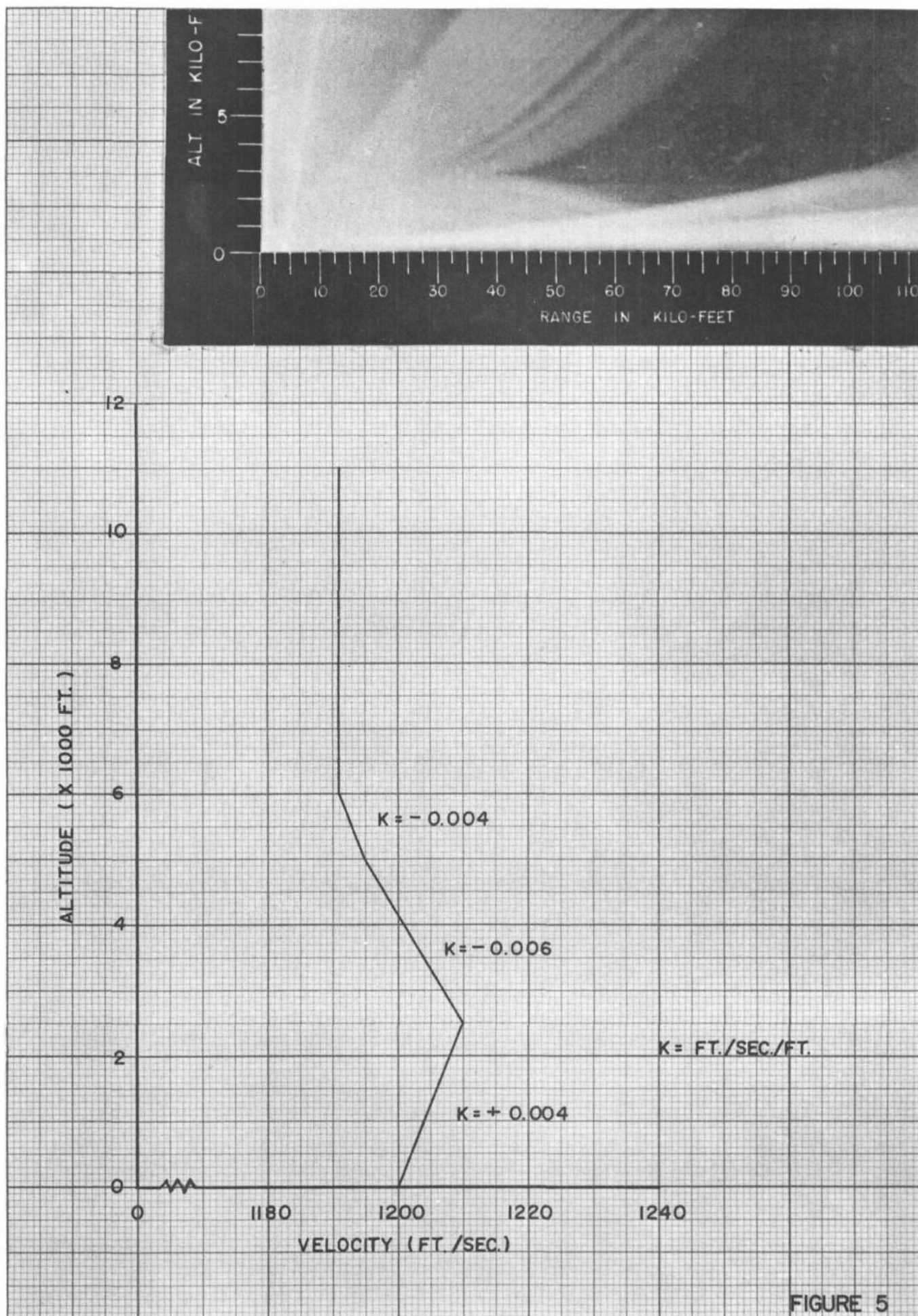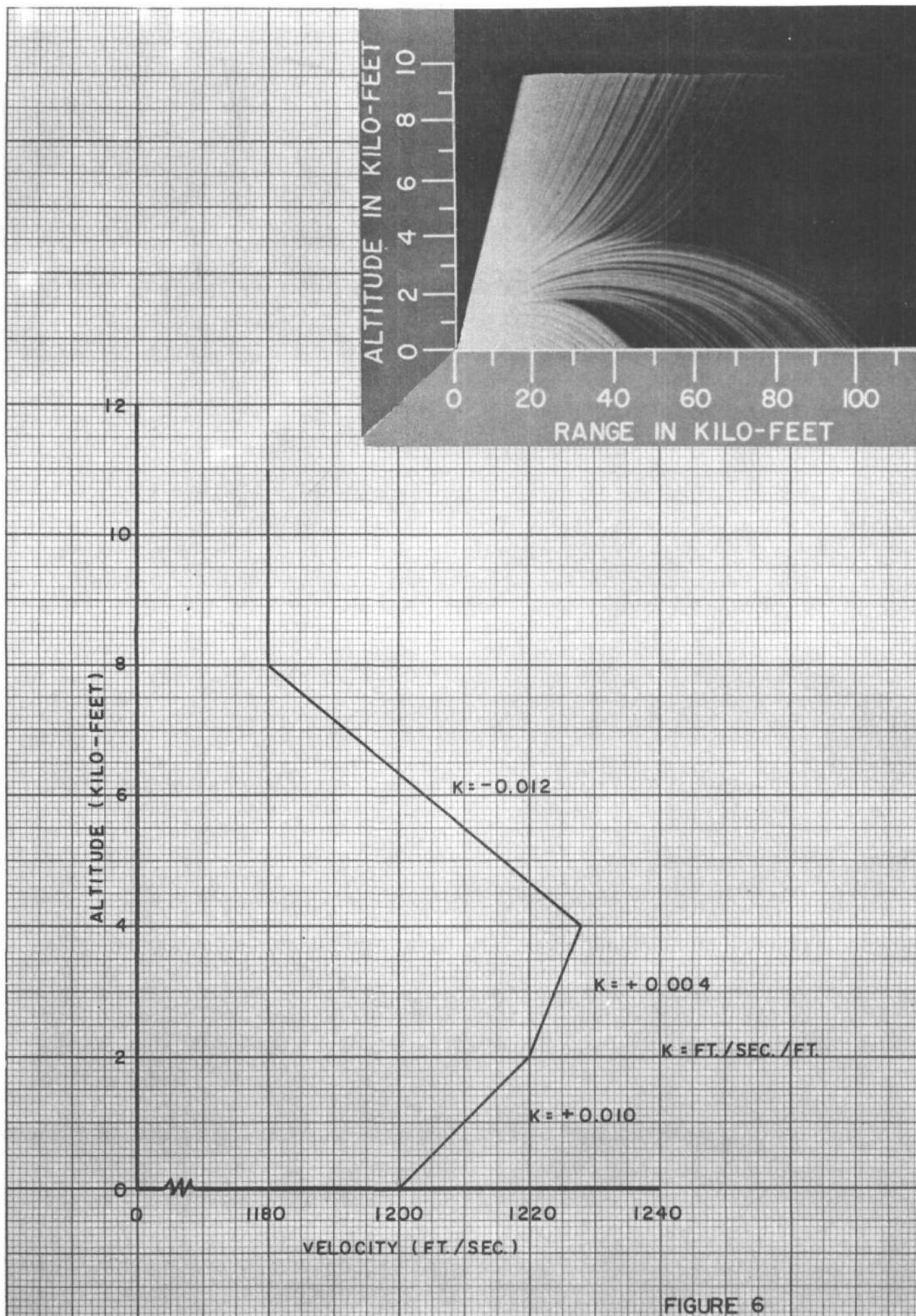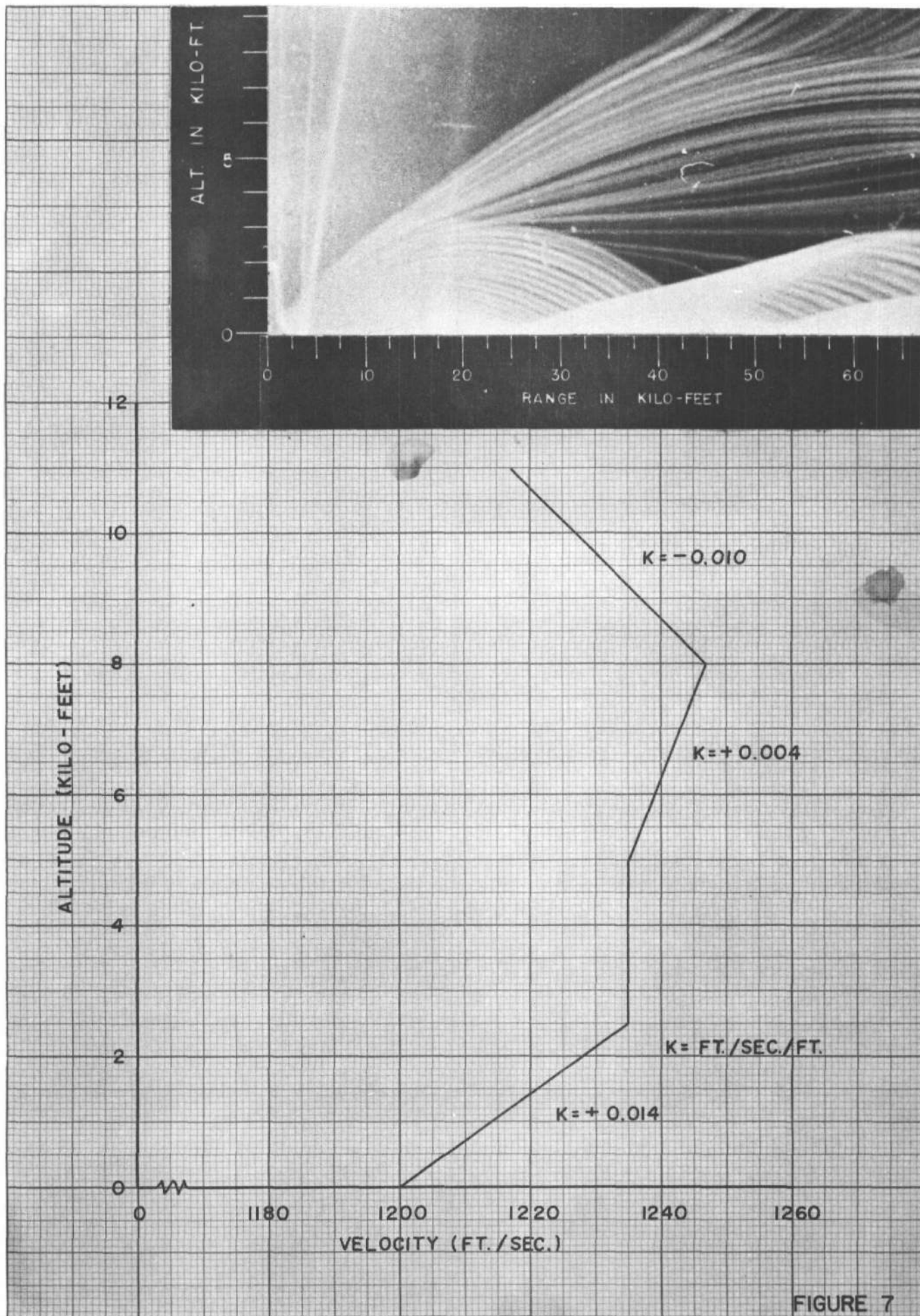
FIGURE 5

FIGURE 6

FIGURE 7

47

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE II

51

FIGURE 12

FIGURE 13

53
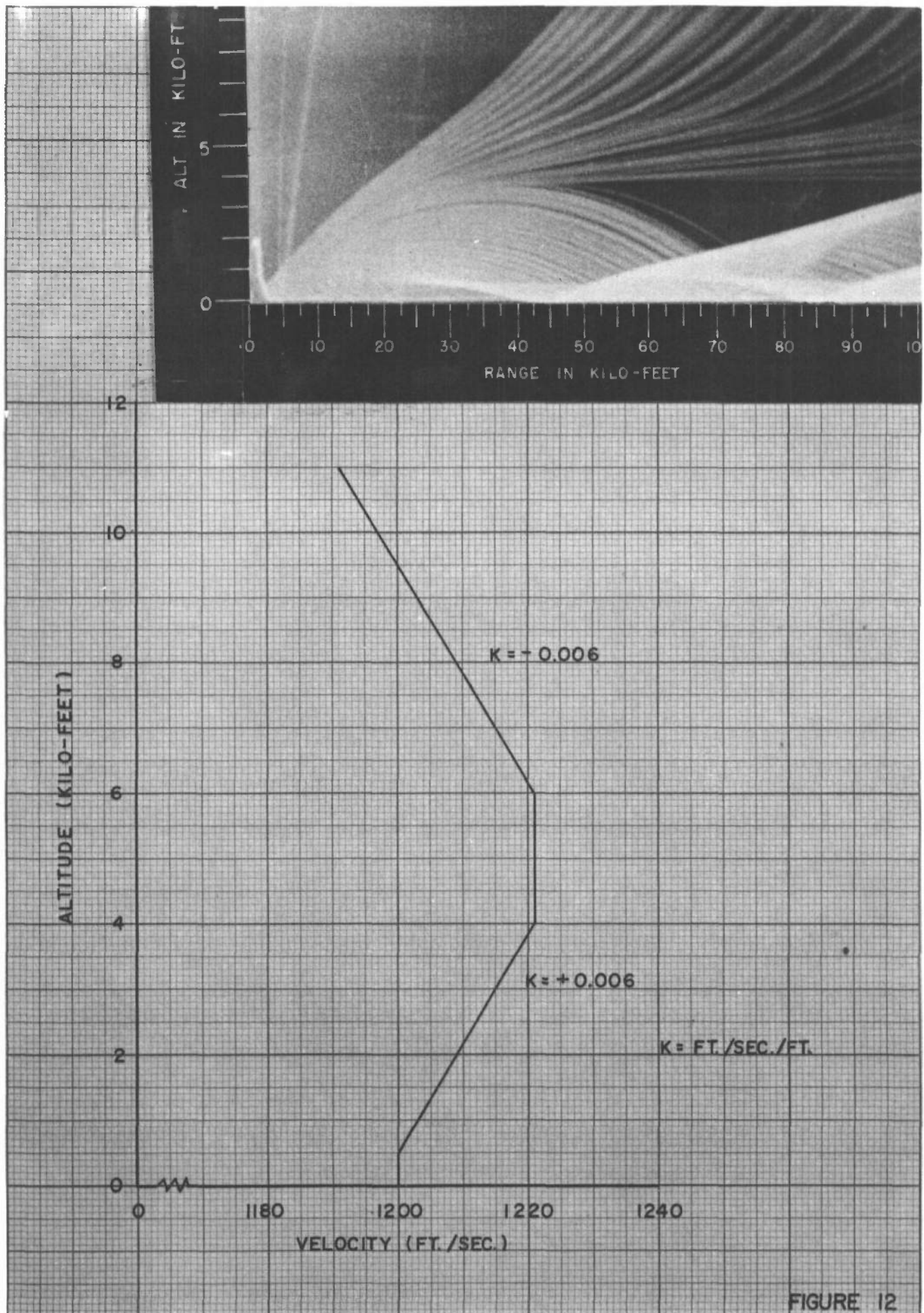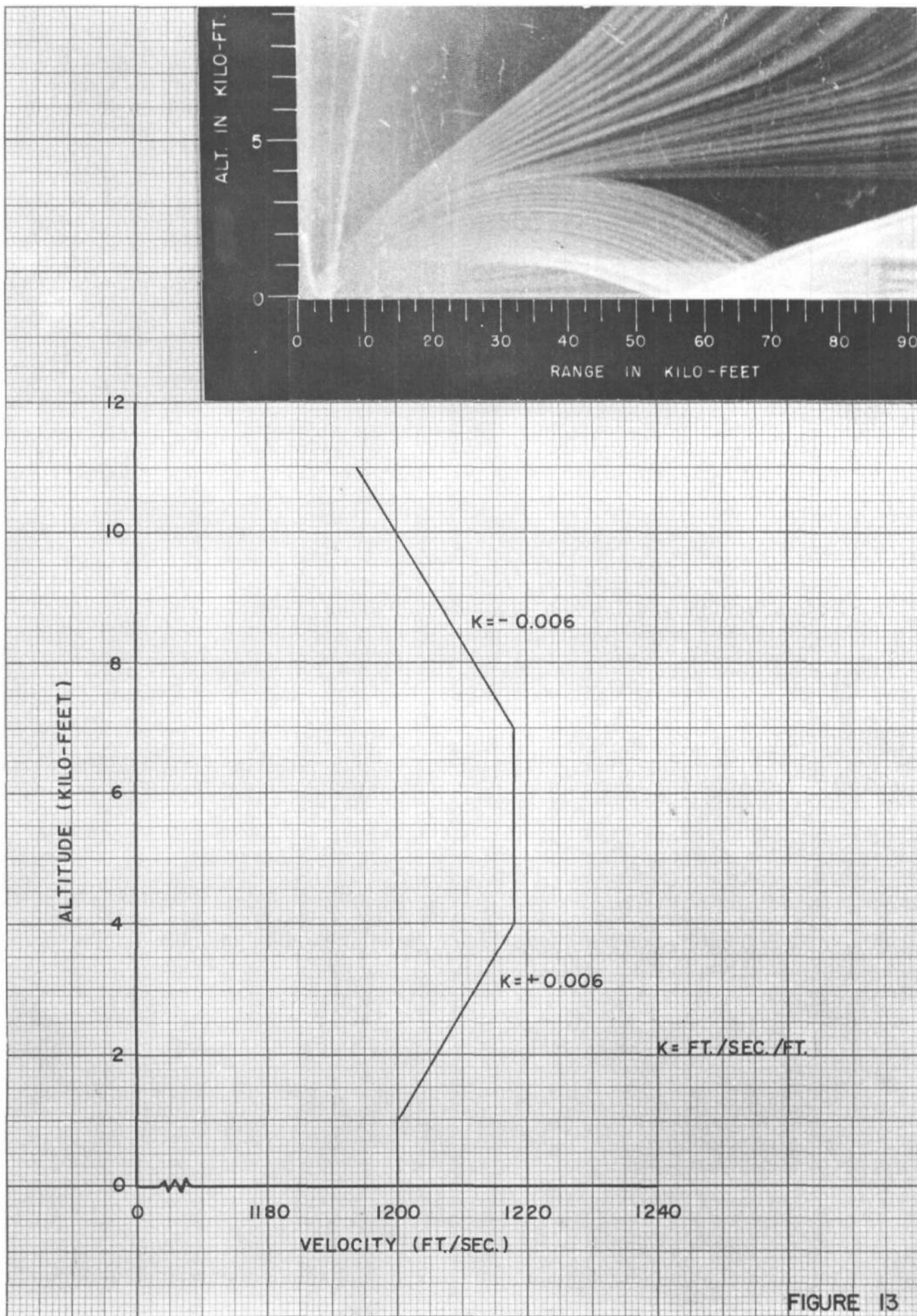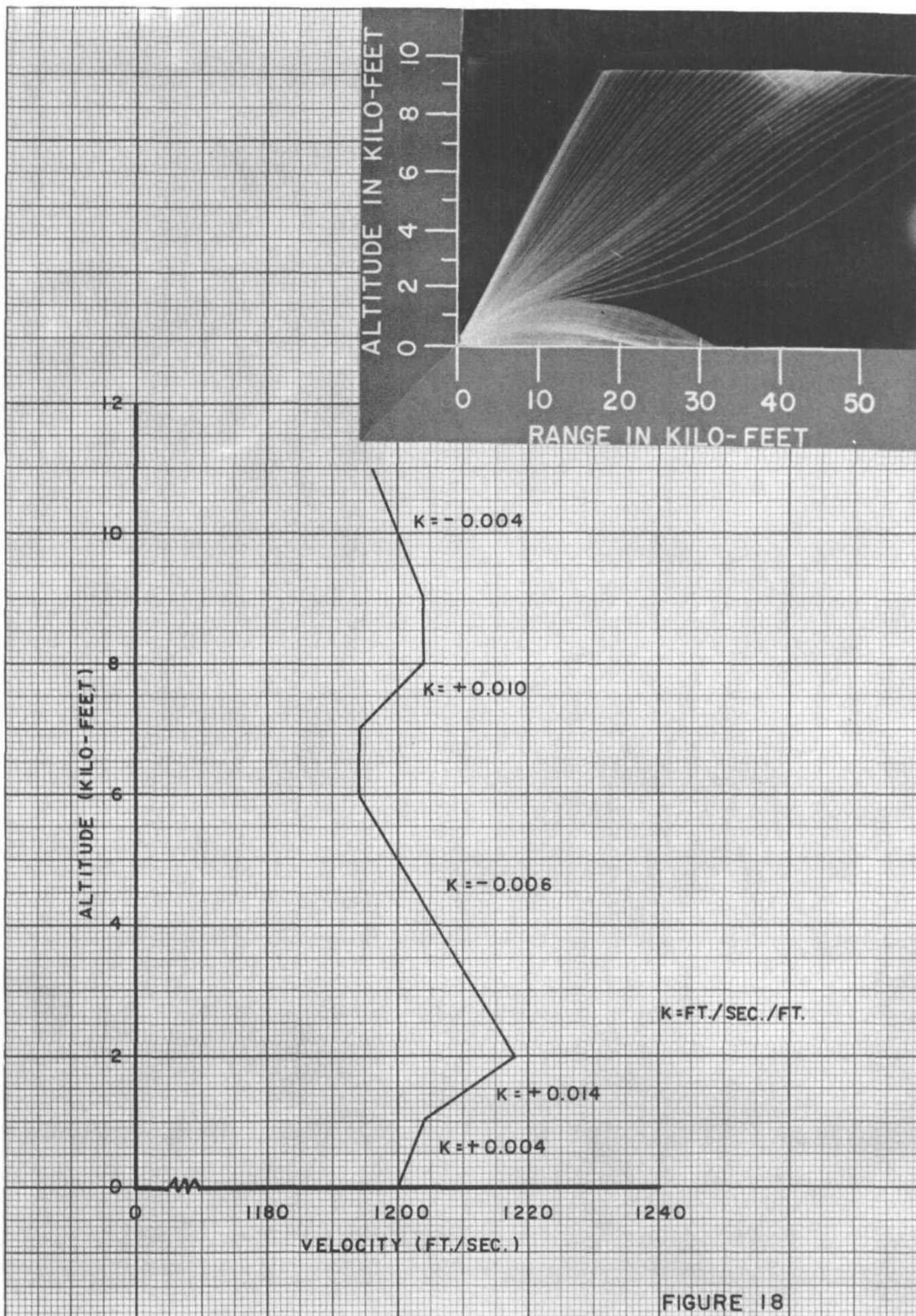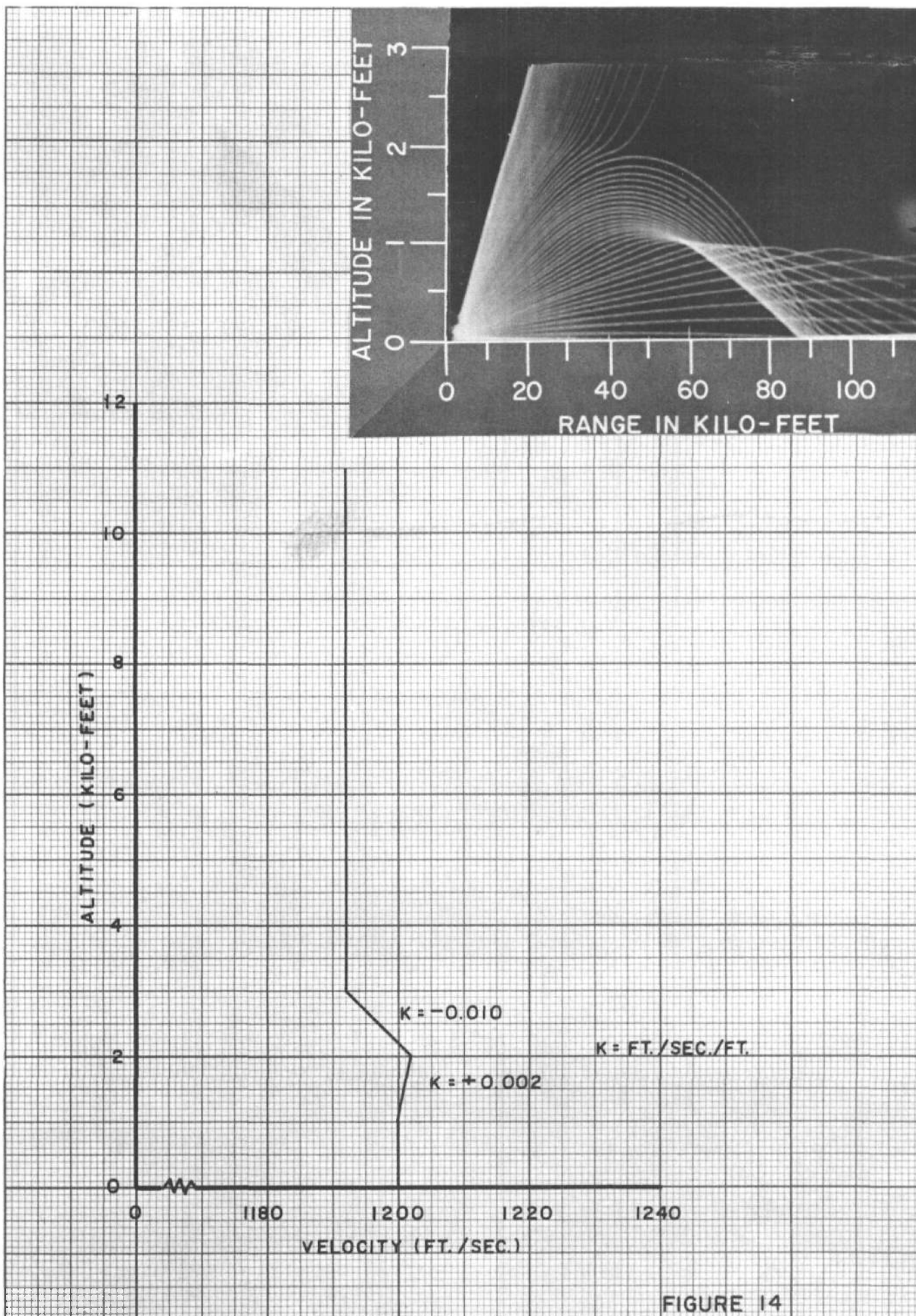
FIGURE 18

FIGURE 14

FIGURE 15

55

FIGURE 16

Graph axes: ALTITUDE (KILO-FEET), VELOCITY (FT./SEC.)

ALTITUDE IN KILO-FEET

RANGE IN KILO-FEET

K = -0.010

K = FT./SEC./FT.

K = +0.016

K = +0.008

FIGURE 17

57
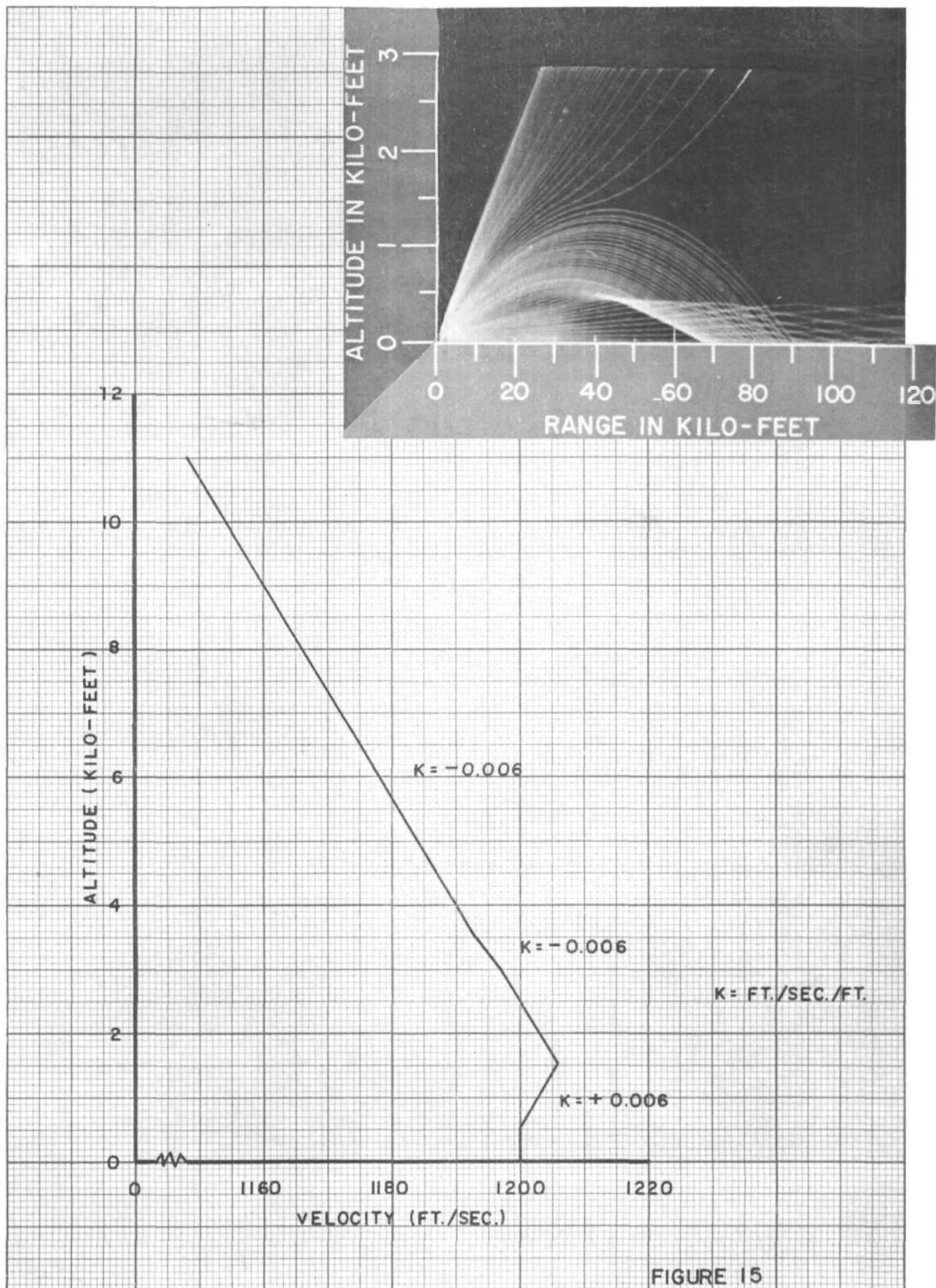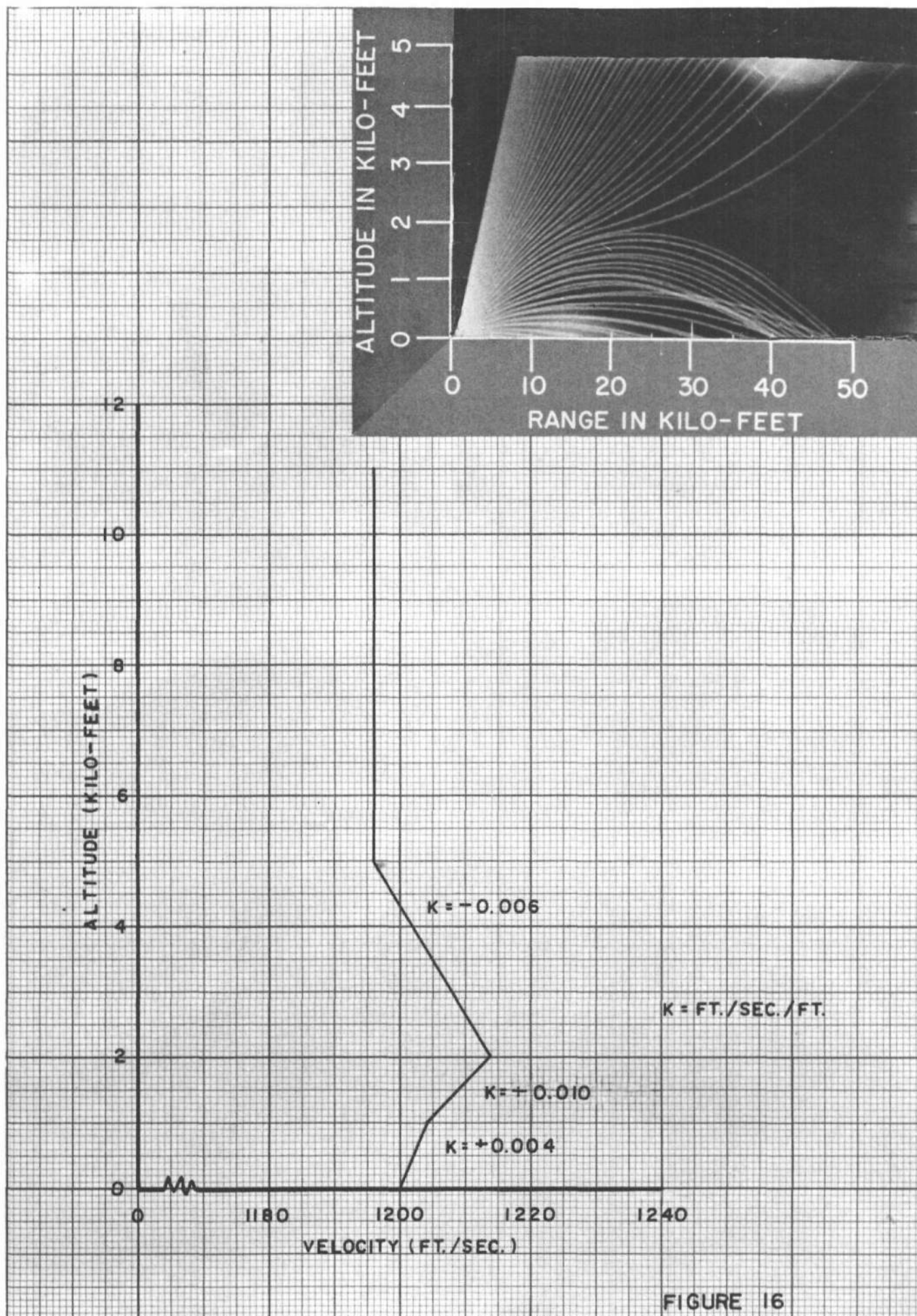
FIGURE 19

59
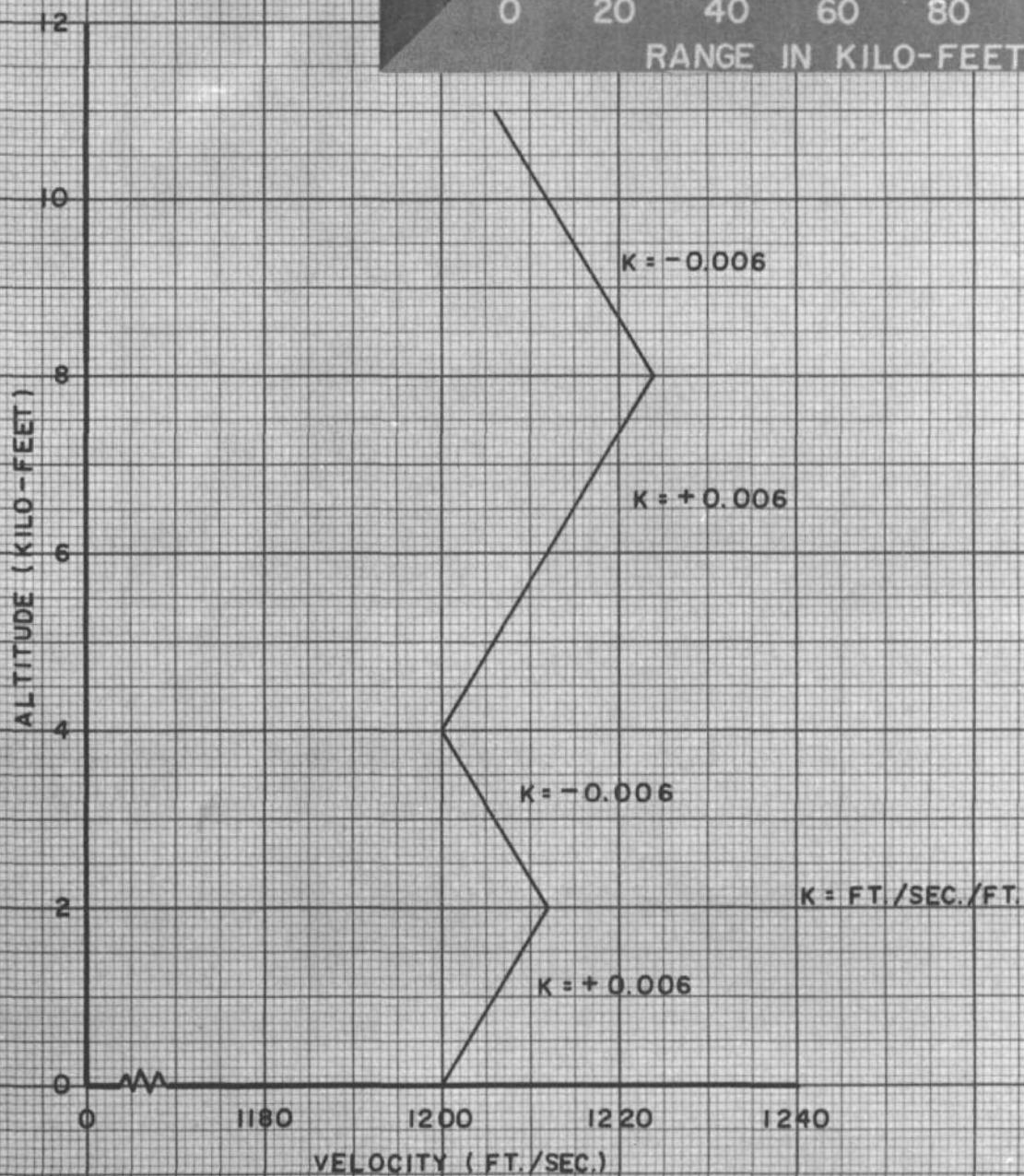
FIGURE 20

FIGURE 21

FIGURE 22

FIGURE 23

FIGURE 24

FIGURE 25

65

ALTITUDE IN KILO-FEET

RANGE IN KILO-FEET

K = − 0.008

K = + 0.006

K = FT./SEC./FT.

K = − 0.004

ALTITUDE (KILO-FEET)

VELOCITY (FT./SEC.)

FIGURE 26

66

ALTITUDE IN KILO-FEET

RANGE IN KILO-FEET

29

K = −.009

K = 0

K = +.008

K = +.020

K = +.014

K = 0

K = −.008

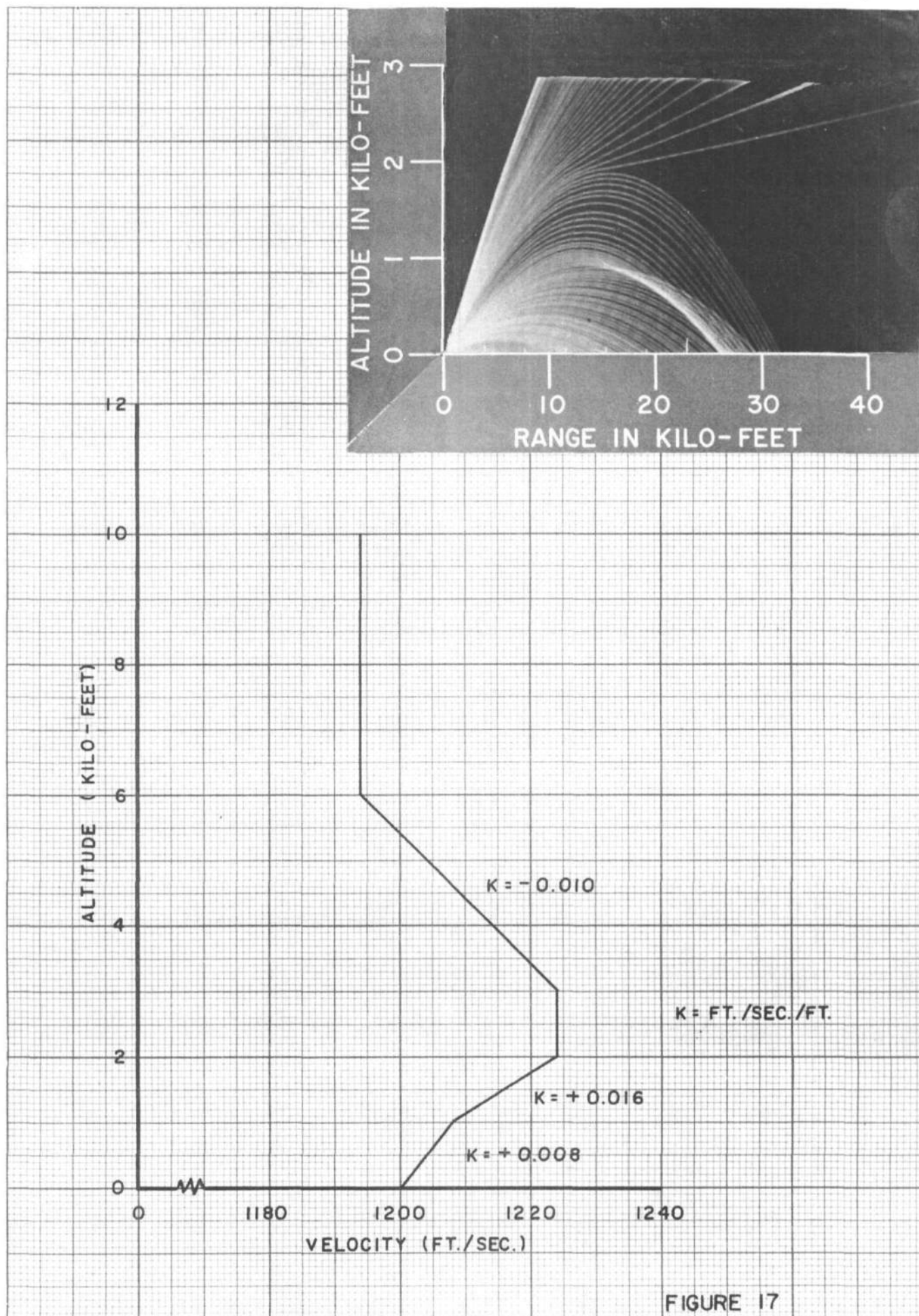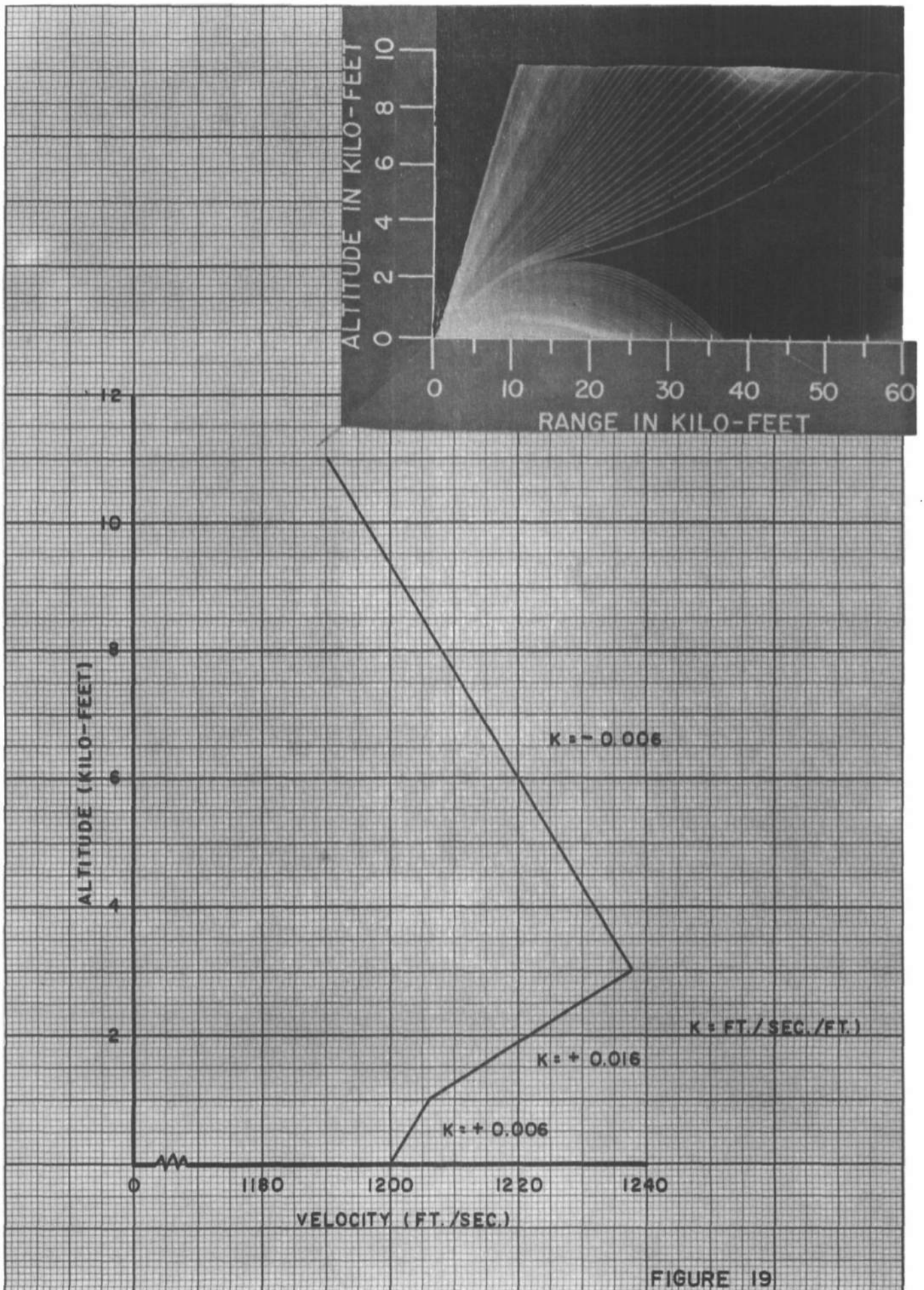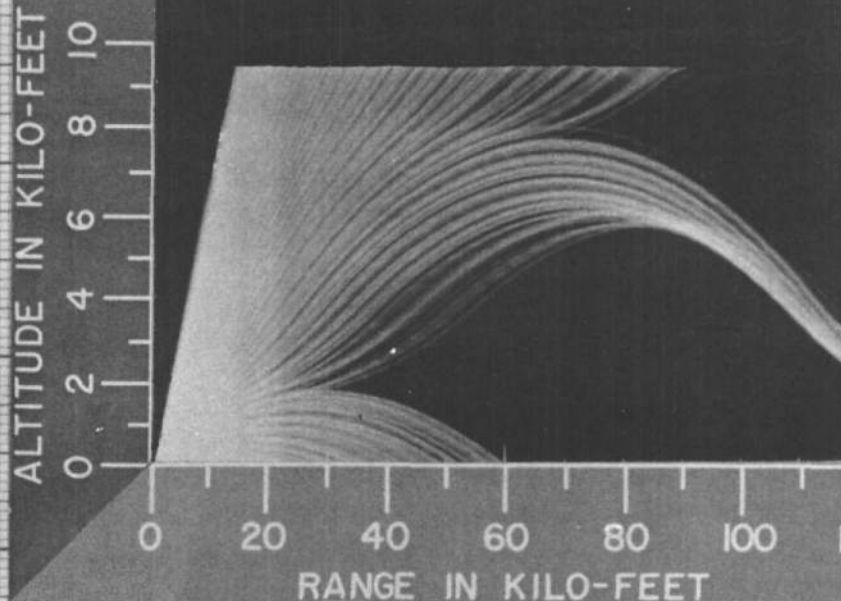K = −.018

K = FT. / SEC. / FT.

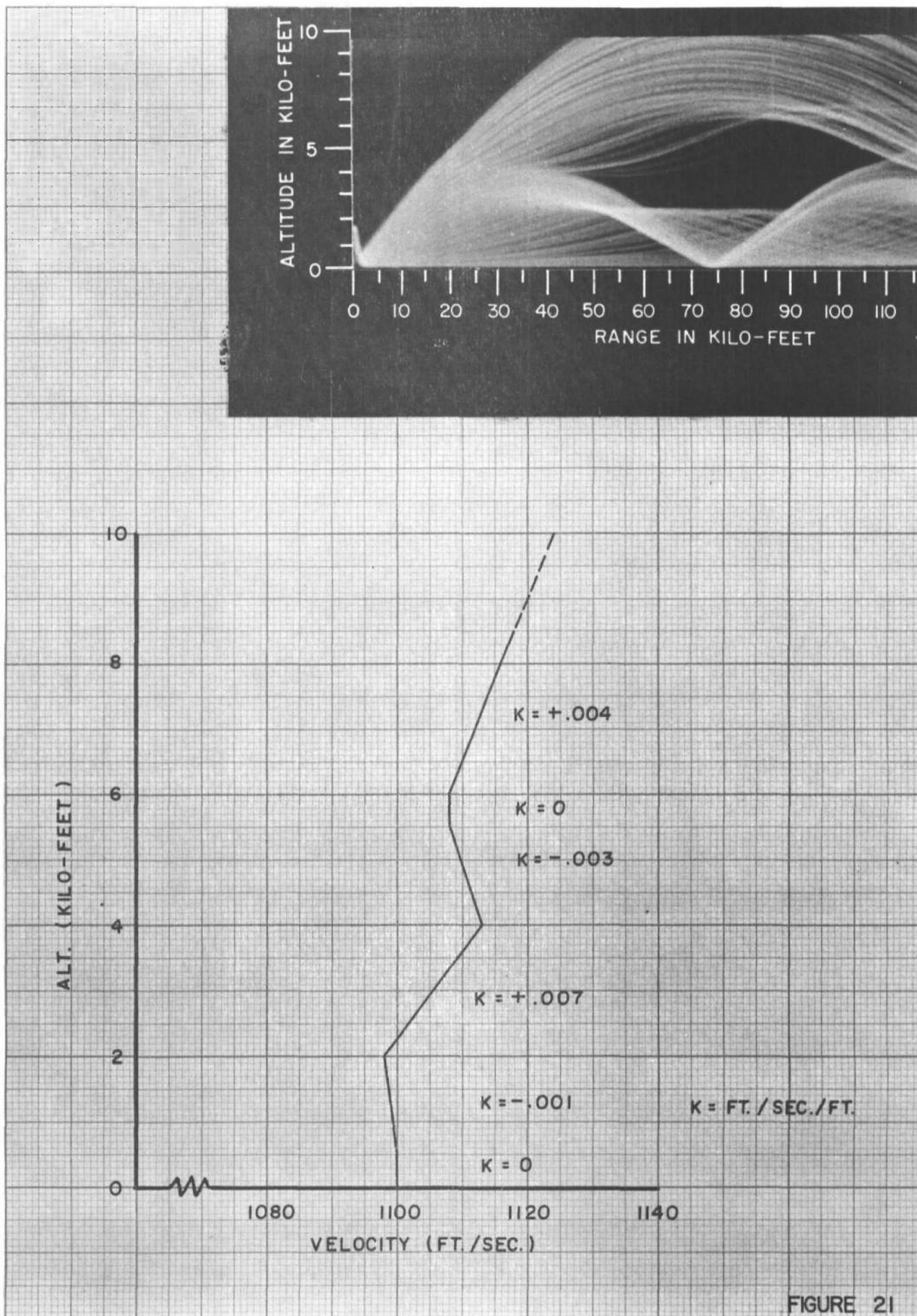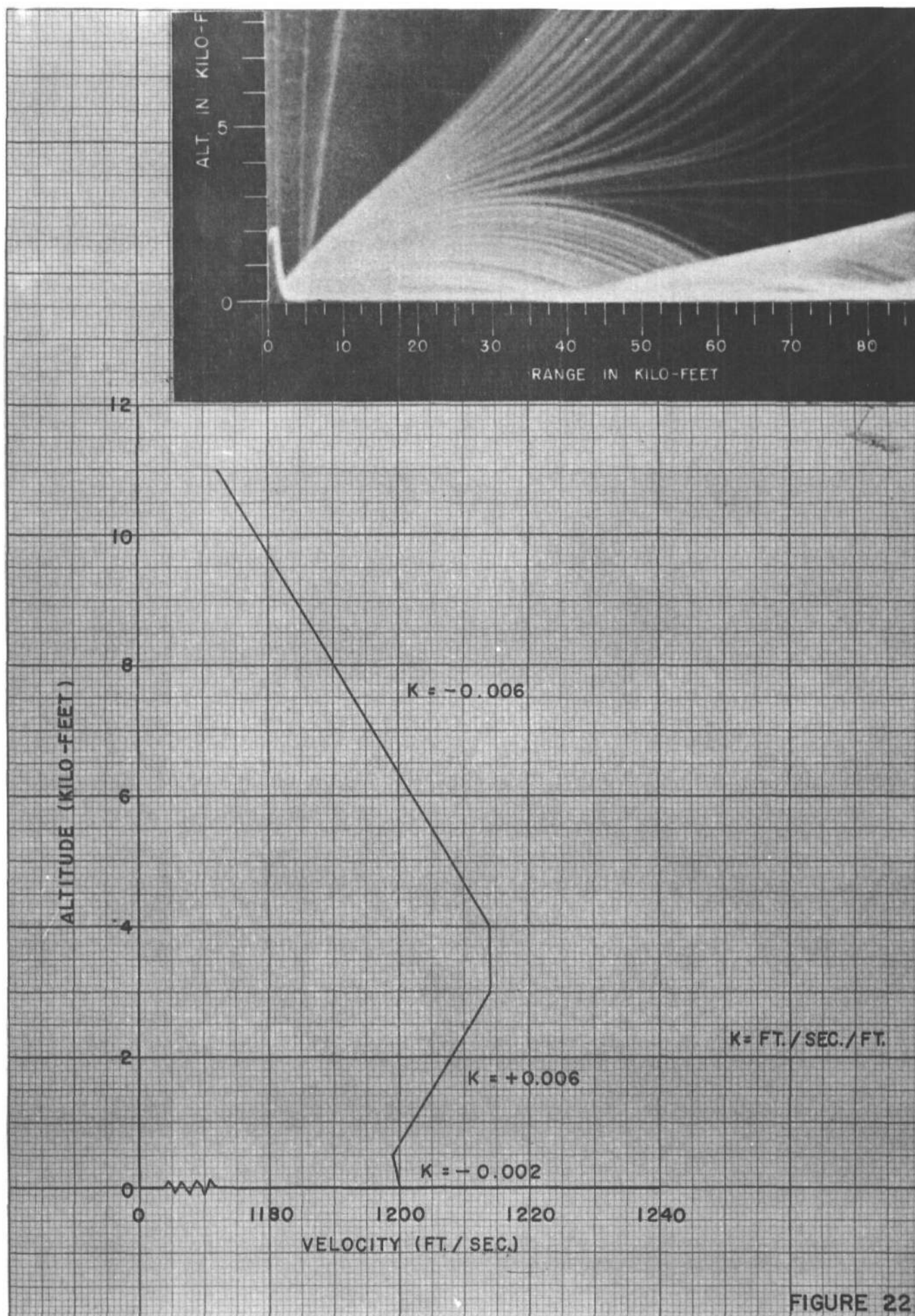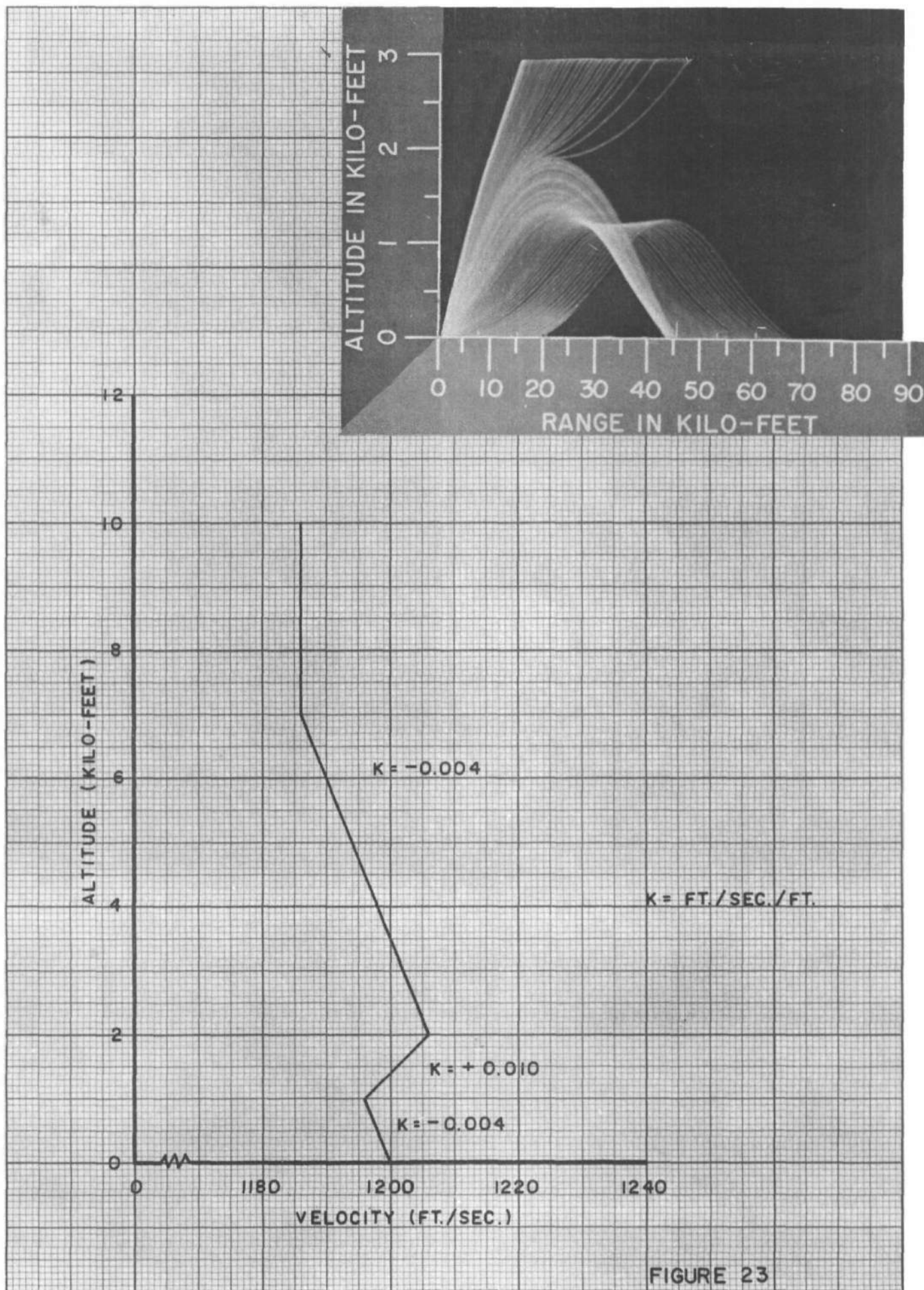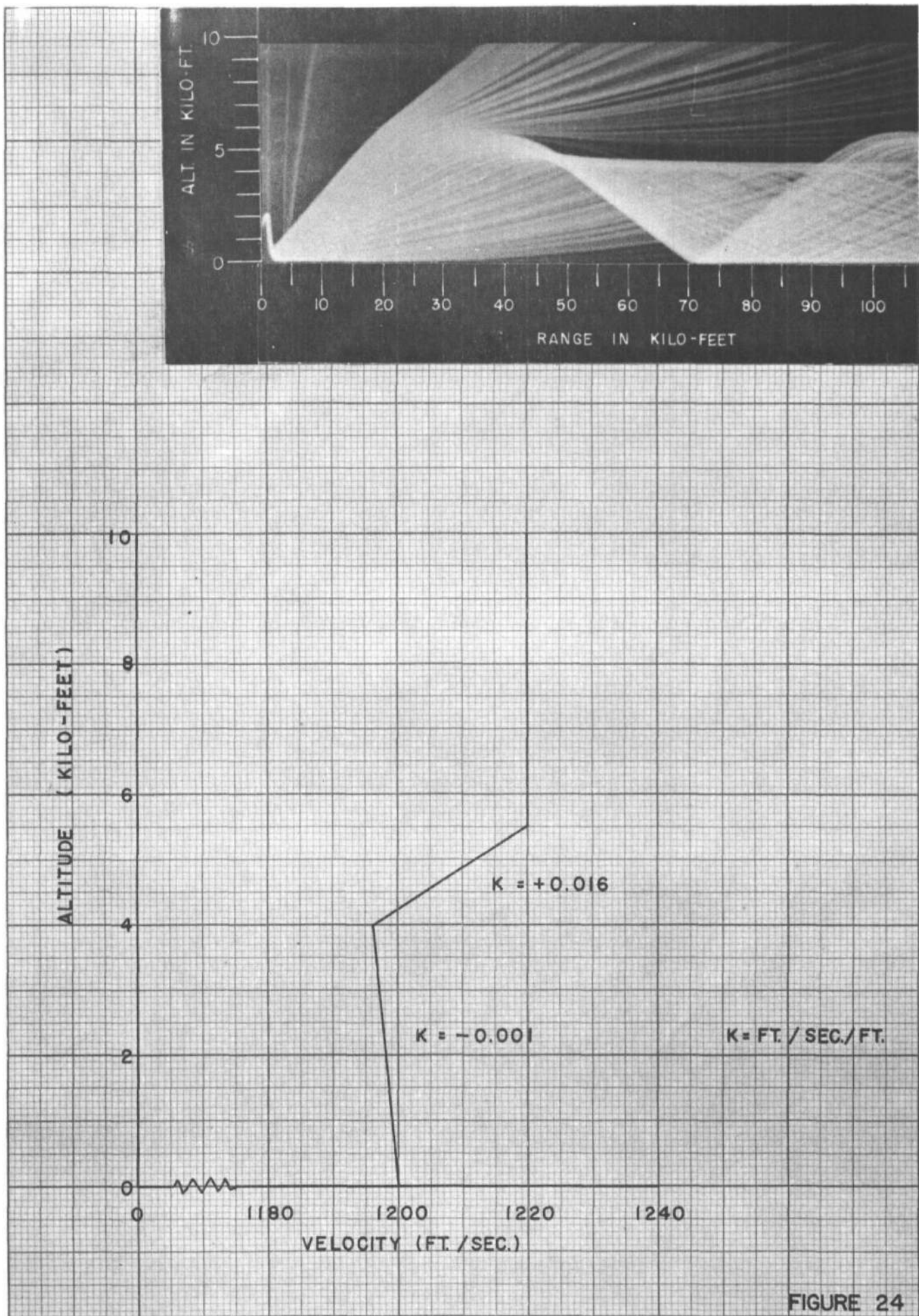ALTITUDE (KILO-FEET)

VELOCITY (FT./SEC.)
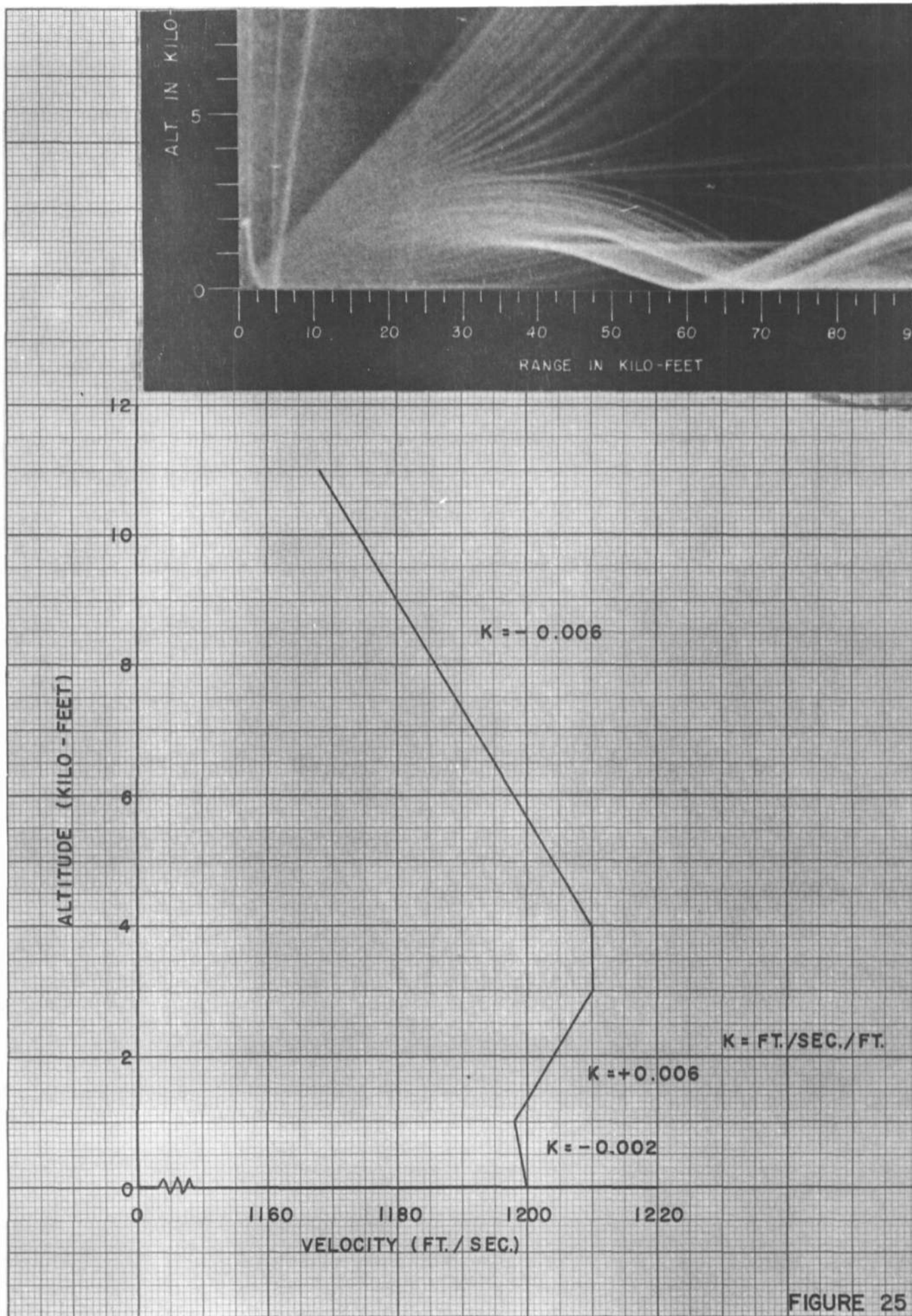
FIGURE 27

67
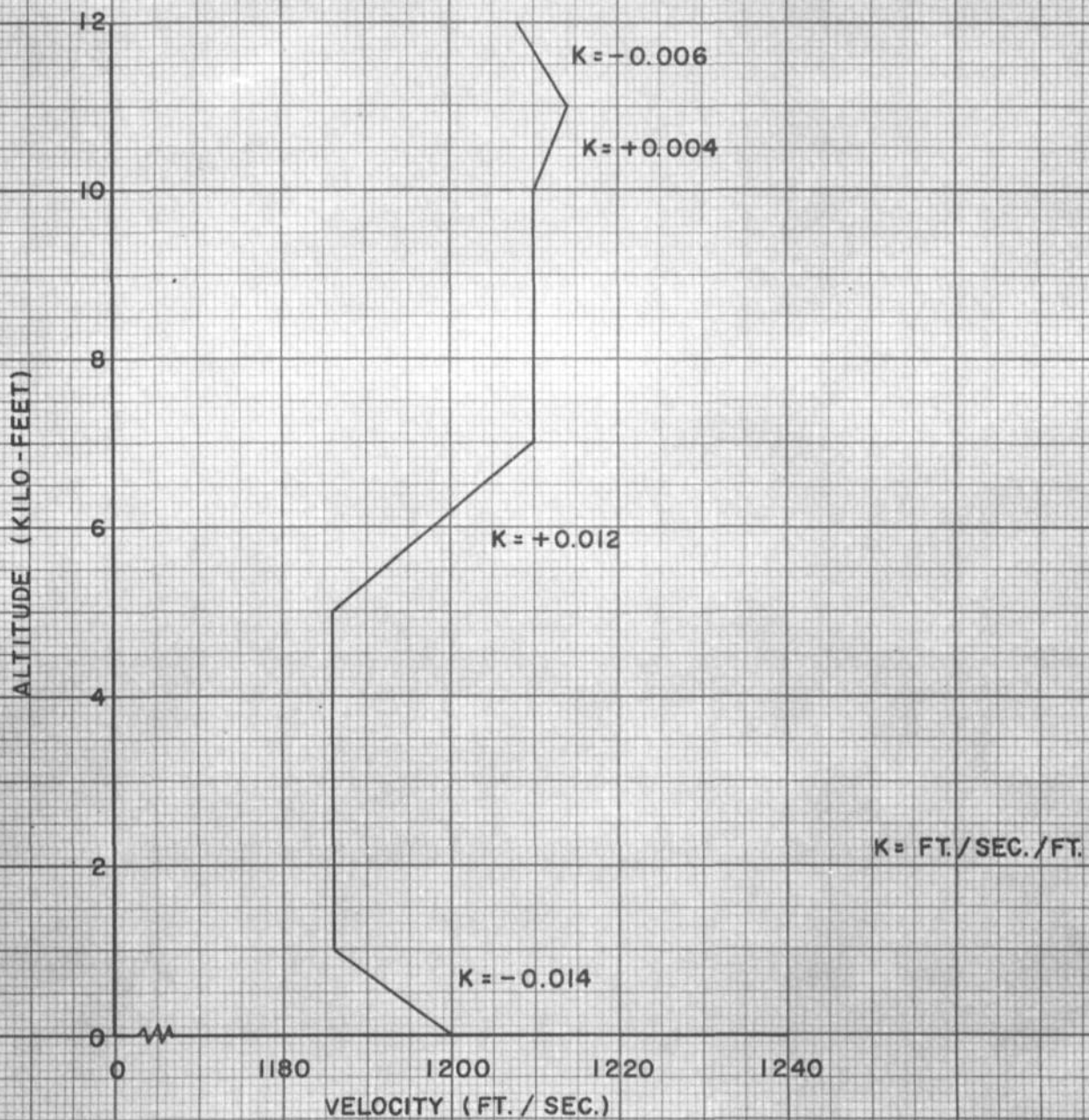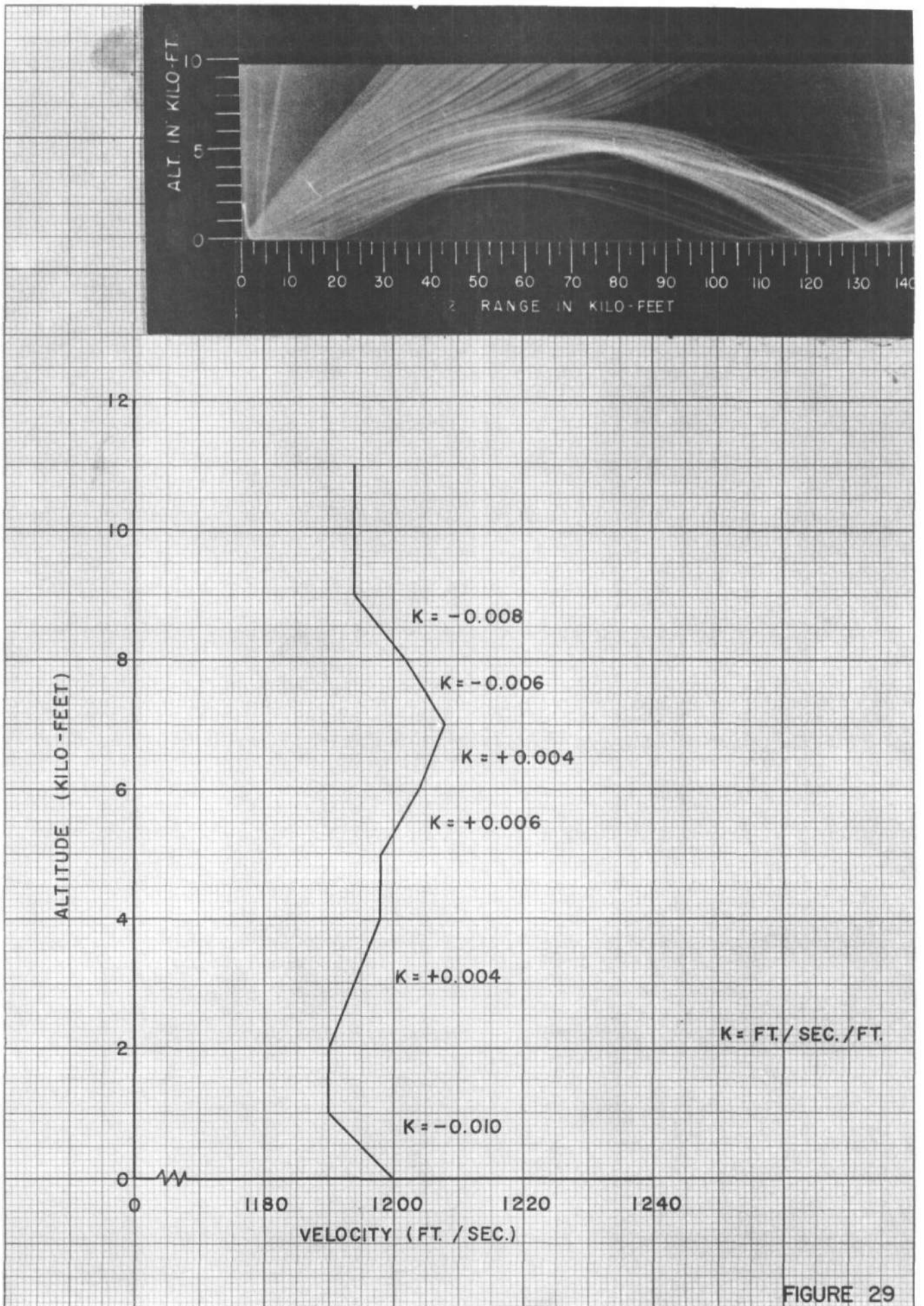
FIGURE 28

FIGURE 29

FIGURE 30

Figure showing photograph of acoustic ray trajectories (ALT. IN KILO-FT. vs RANGE IN KILO-FEET) above a graph of ALTITUDE (KILO-FEET) vs VELOCITY (FT./SEC.) with velocity profile segments labeled K = -0.006, K = +0.012, K = -0.006, K = -0.004, K = +0.010, K = -0.010, and K = FT./SEC./FT.
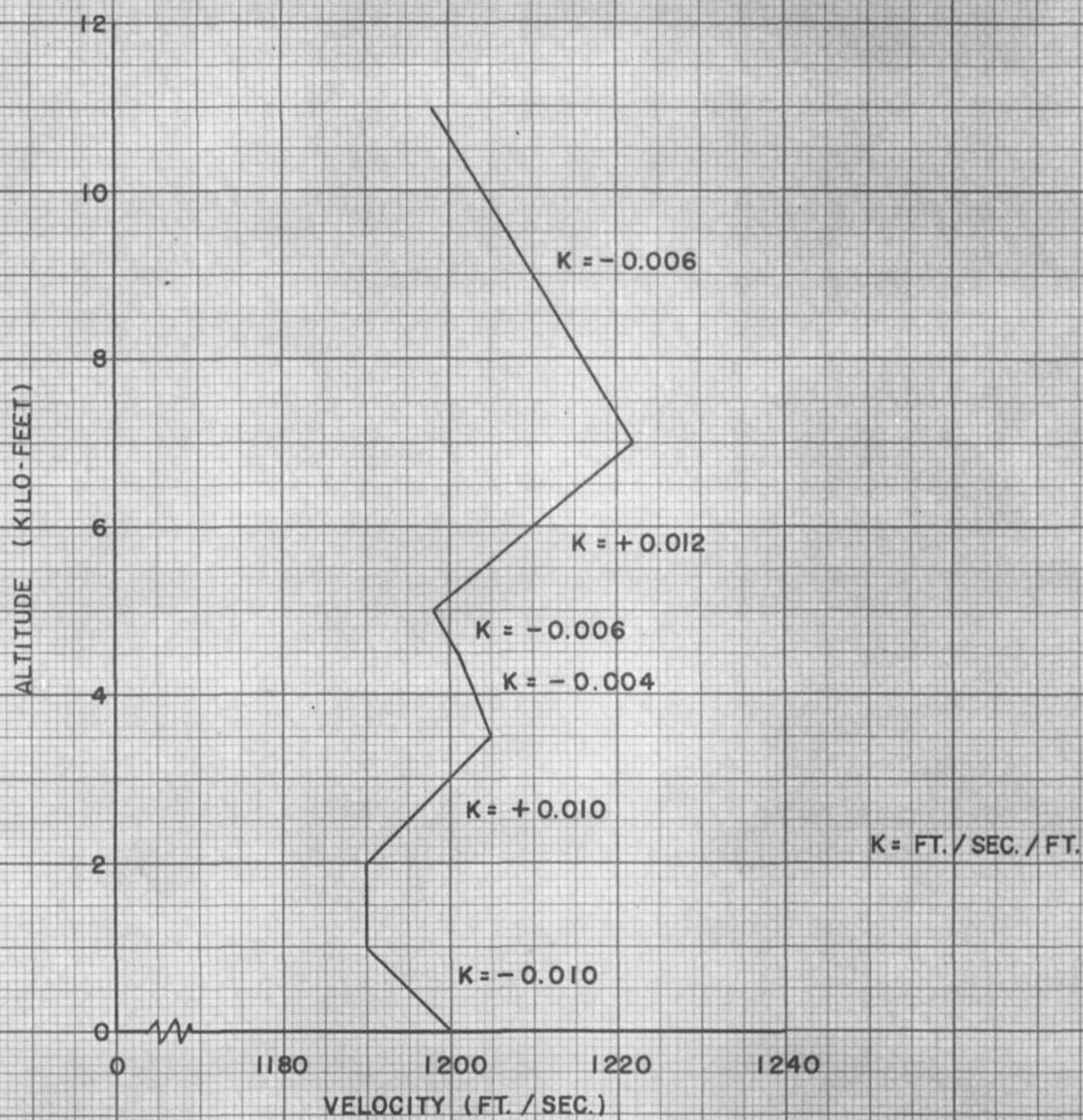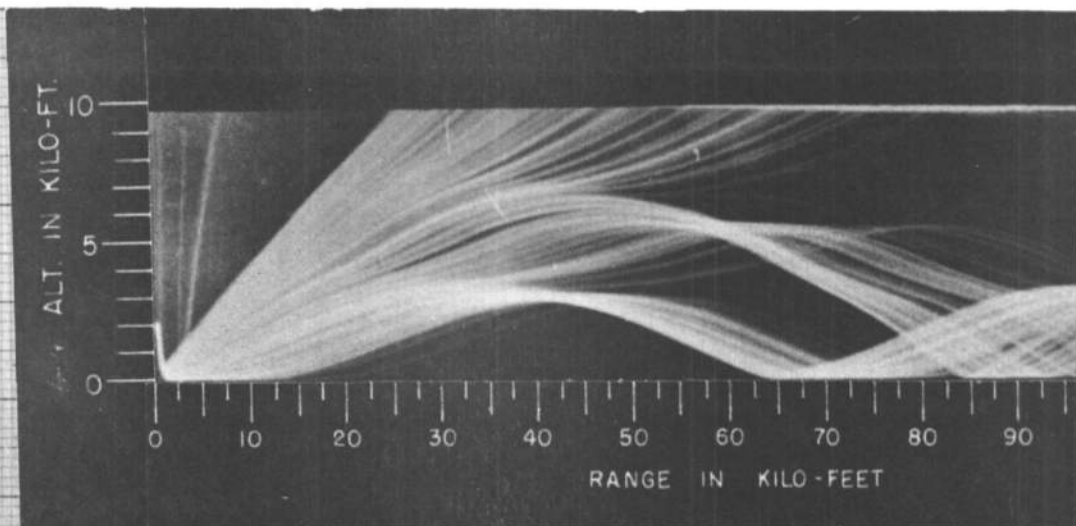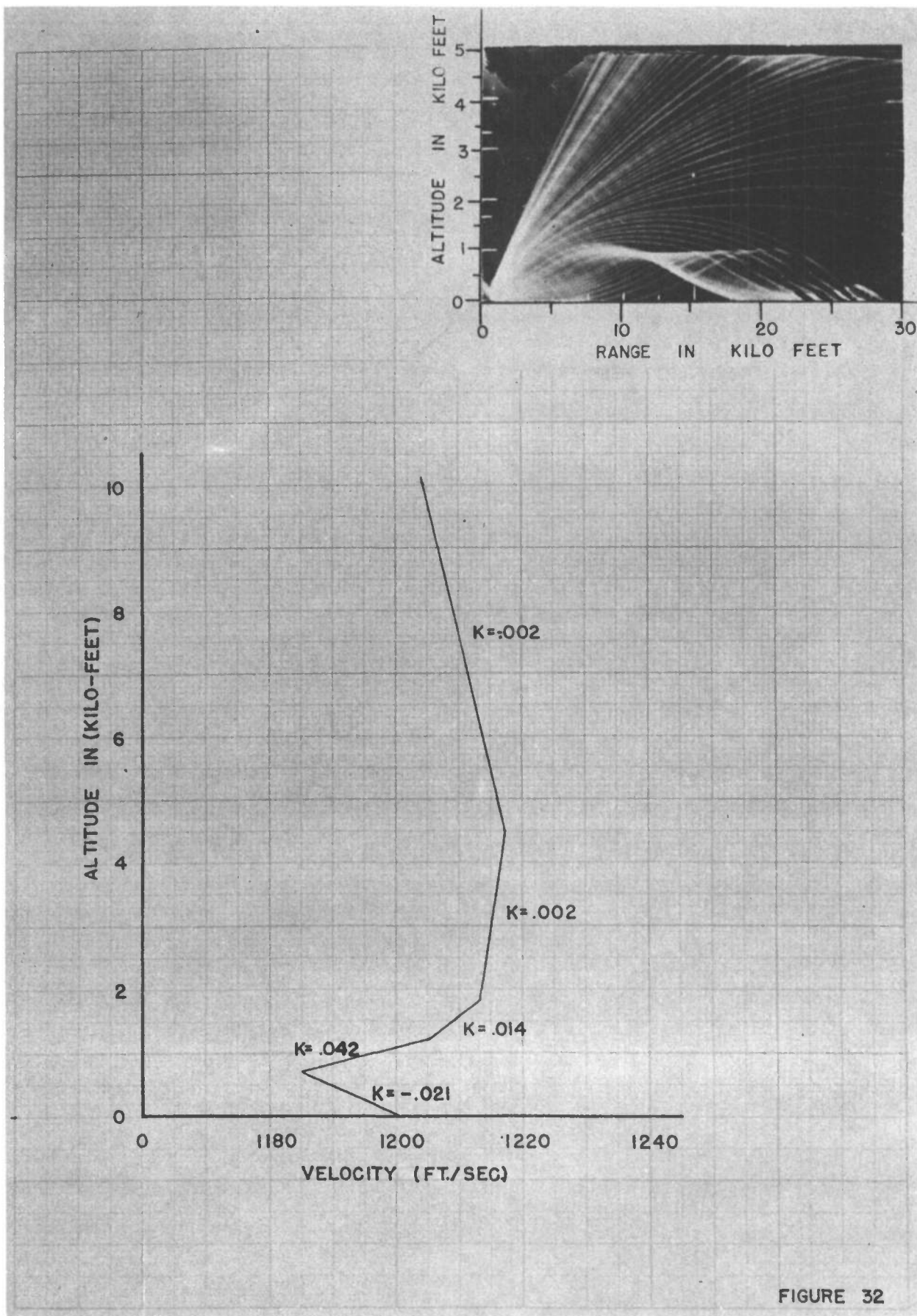
FIGURE 31

FIGURE 32

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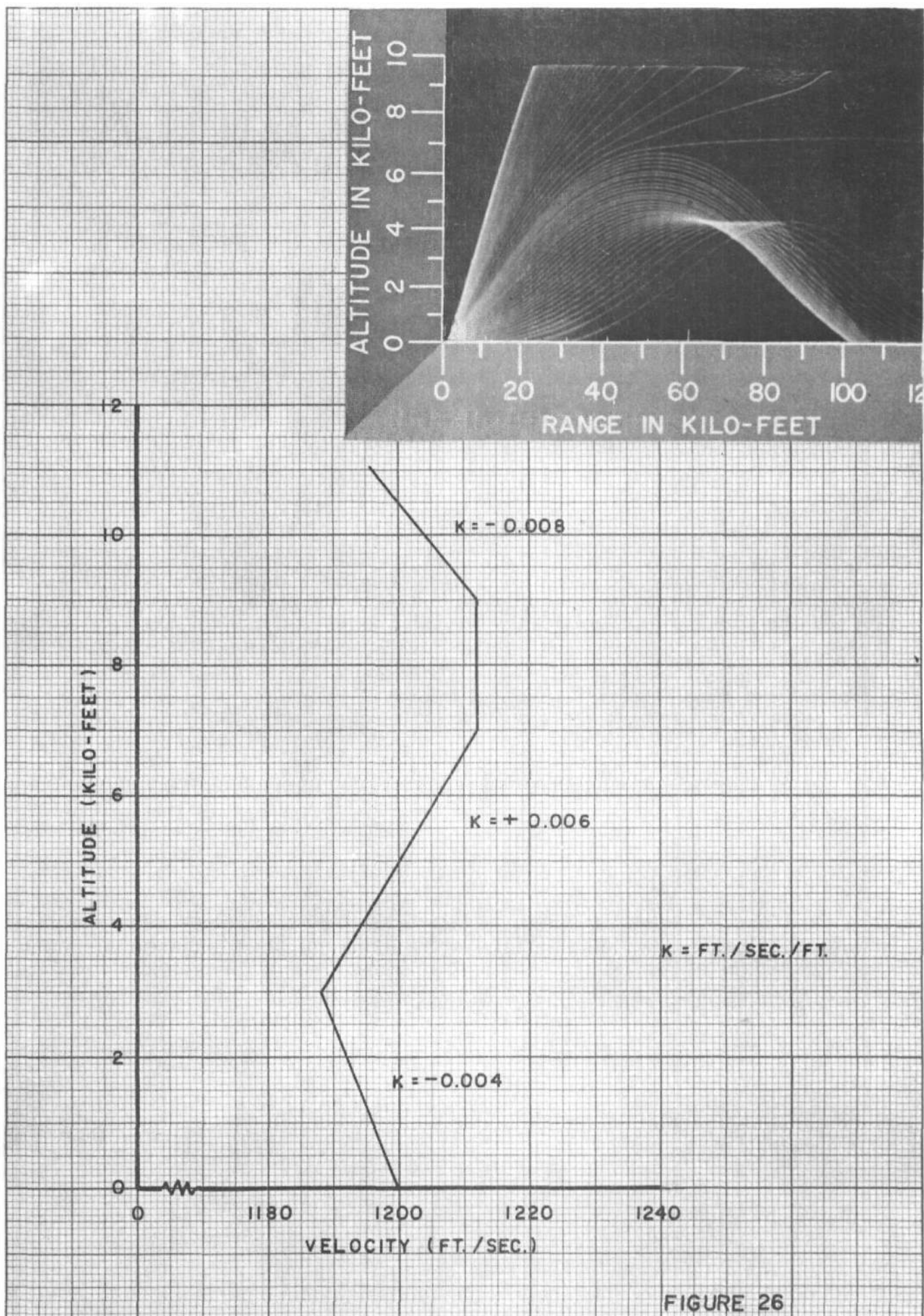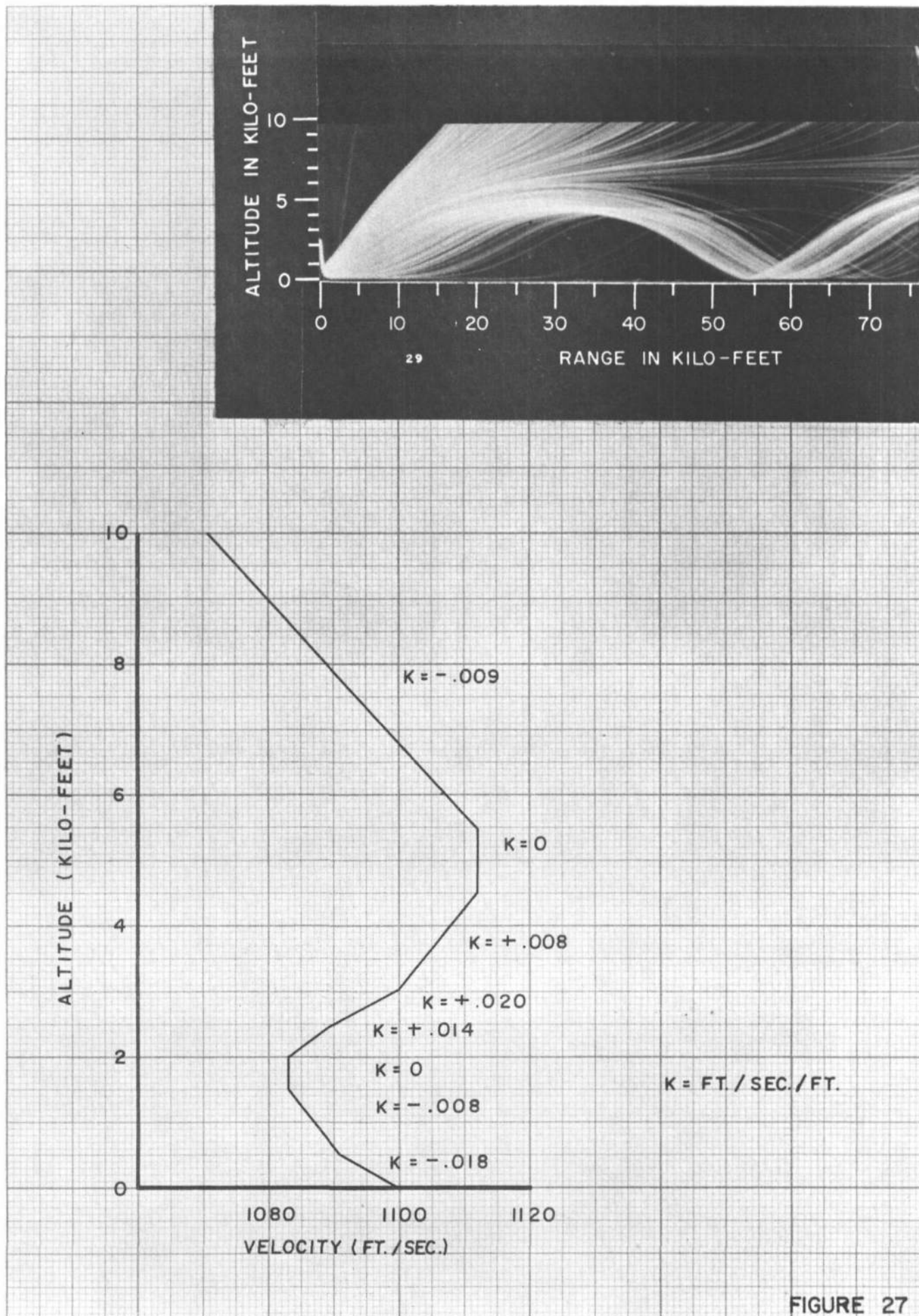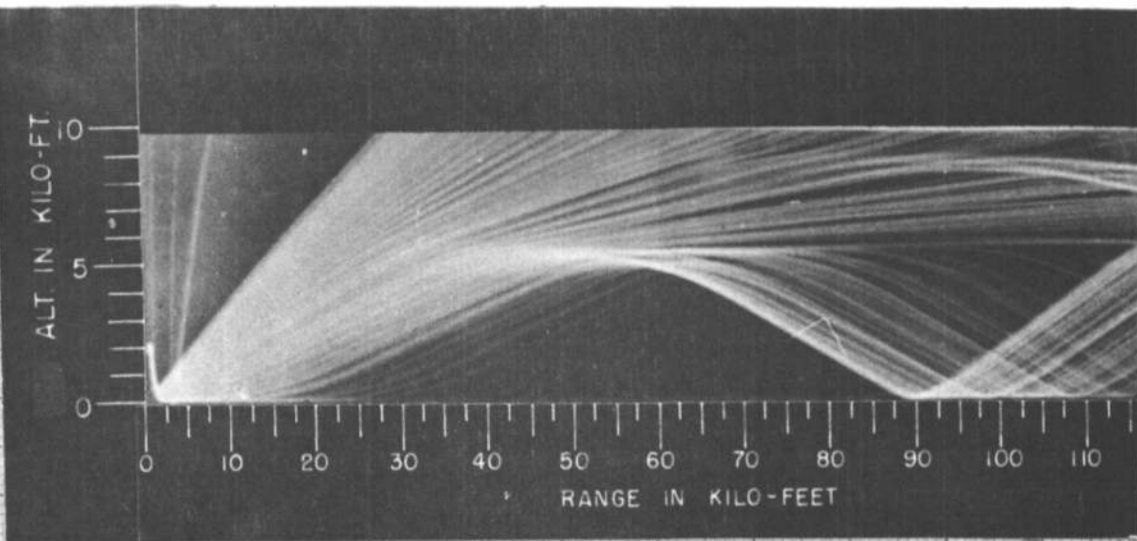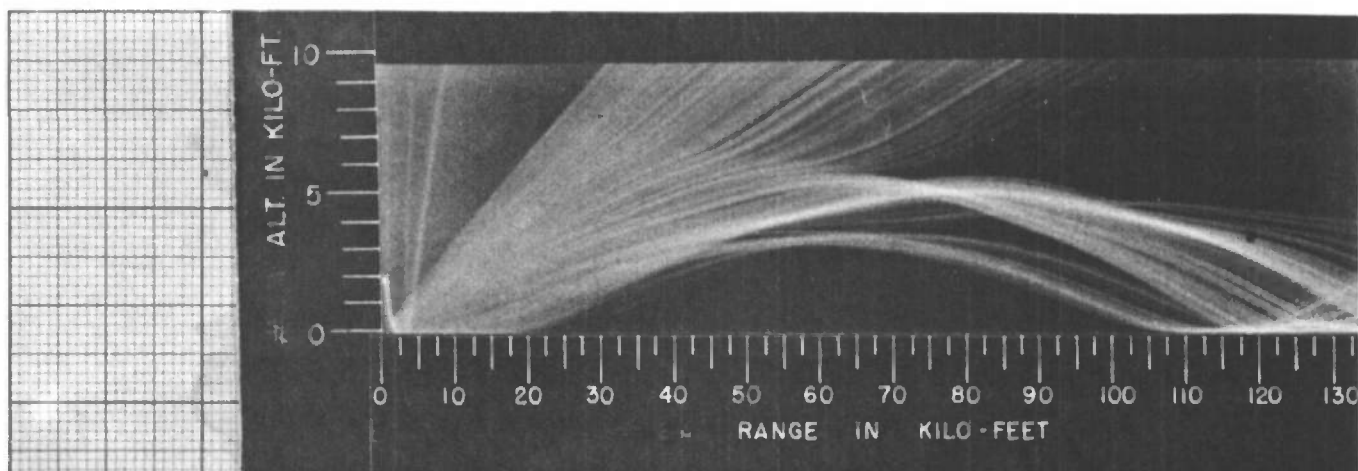| No. of Copies	Organization	No. of Copies	Organization
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